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EVALUATION OF SO_2 AND NO_x EMISSION IN FLUIDIZED BED COMBUSTION

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EXECUTIVE SUMMARY

This report examines the effects of fuel type, facility and operating parameters on SO_2 and NO_x emissions from three bubbling FBC pilot plants, two circulating FBC pilot plants and an industrial bubbling FBC heating plant. The relationships between the NO_x and CO emissions, the NO_x and SO_2 emissions, and the SO_2 and CO emissions have also been examined. The data are summarized from results of 40 separate test programs providing information for twelve coals, a coal/water slurry, three cokes and four heavy oils.

In tests without sorbents, the SO_2 emissions are found to be proportional to the sulphur content of the fuel. Approximately 71.5% of the fuel sulphur is emitted as sulphur-containing gaseous pollutants.

In tests with limestone addition, the standardized SO_2 emission, which is defined as the SO_2 emission divided by the sulphur content of the fuel, is found to depend largely on Ca/S molar ratio. Fly ash recycle and finely sized limestone enhance the efficiency of sorbent utilization. The effect of bed temperature is significant only when it exceeds 1050 deg. C. Circulating FBC systems are found to be more effective for sulphur capture in tests with fine solid fuels and liquid fuels due mainly to the longer contact time between solids and gases.

An empirical model based on a review of previous models and the available data has been proposed to describe the SO_2

emission:

$$E_1 = 2*B_2*\exp[-B_1*(Ca/S)]$$

where E_1 is the standardized SO_2 emission, and B_1 and B_2 are coefficients.

In all the tests reviewed, the NO_x emissions have been found to decrease as the CO emissions increase. It has also been found that the NO_x emissions are proportional to the nitrogen content of the fuel, indicating, on average, a conversion of 13.8% of fuel nitrogen to NO_x.

The effects of excess oxygen and bed temperature appear to be facility dependent. Four of the FBC units showed increasing NO_x emissions with increasing bed temperature while the other two showed no correlation. In only two of the pilot plants the NO_x emissions increased with excess oxygen. There appears to be no correlation between NO_x emissions and excess oxygen for the other three pilot plants. The NO_x emissions observed at the industrial heating plant are significantly higher than those observed at the five pilot plants, probably because the heating plant employs unusually high levels of excess oxygen, which in turn results in unusually low levels of CO, However, at this plant, NO_x emissions decrease slightly with increasing excess oxygen, probably because increased air flow increases the elutriation of char fines, leading to somewhat higher levels of CO in the freeboard.

A study of the effect of the Ca/S molar ratio indicates

a strong correlation of the increase of NO_x emission to an increase in the Ca/S molar ratio for one of the circulating FBC units. There appears to be little correlation in the other five FBC units studied. However, a decrease in NO_x emission with Ca/S molar ratio has been observed in a few test programs.

ABRÉGÉ

Dans ce rapport nous examinons les effets des différents paramètres relatifs au type de combustible, aux installations et au type d'exploitation sur les émissions de SO_2 et de NO_x de trois fournaises pilotes à lit fluidisé bouillonnant, de deux fournaises pilotes à lit fluidisé circulant et d'une fournaise industrielle de chauffage à lit fluidisé bouillonnant. Les rapports entre les émissions de NO_x et de CO, les émissions de NO_x et de SO_2 et les émissions de SO_2 et de CO ont également été examinés. Les données sont résumées à partir des résultats de 40 programmes de tests indépendants et fournissent des renseignements pour douze charbons, un mortier charbon/eau, trois cokes et quatre huiles lourdes.

Dans les tests effectués sans absorbant, on a constaté que les émissions de SO_2 étaient proportionnelles au contenu en soufre du combustible. Environ 71,5% du soufre contenu dans le combustible se dégage sous forme de polluants gazeux sulfureux.

Dans les tests effectués avec addition de pierre calcaire, on a constaté que l'émission standardisée de SO_2, que l'on définit comme étant l'émission de SO_2 divisée par le contenu en soufre du combustible, dépendait en grande partie du rapport molaire Ca/S. Le recyclage des escarbilles et l'utilization du calcaire finement broyé améliorent l'efficacité de l'utilisation de l'absorbant. La température

du lit n'a d'effet significatif que lorsqu'elle dépasse 1050 degrés C. On a constaté que, lors des tests effectués avec des combustibles solides fins et avec des combustibles liquides, les fournaises à lit fluidisé circulant étaient plus efficaces pour retenir le souffre; cela est dû principalement au fait que les solides et les gaz restent plus longtemps en contact.

Un modèle empirique basé sur examen de modèles préalables et sur les données disponibles a été proposé pour décrire l'émission de SO_2:

$$E_1 = 2*B_2*\exp[-B_1*(Ca/S)]$$

E_1 représentant l'émission standardisée de SO_2 et B_1 et B_2 étant les coefficients.

Dans tous les tests étudiés, on a constaté que les émissions de NO_x diminuaient lorsque les émissions de CO s'augmentaient. On a également constaté que les émissions de NO_x étaient proportionnelles au contenu en azote du combustible, ce qui indique une transformation en NO_x de 13,8%, en moyenne, de l'azote contenue dans le combustible.

Les effets d'un excès d'oxygène et de la température du lit semblent dépendre du type d'installation. Dans le cas de quatre des fournaises à lit fluidisé, on a constaté une augmentation des émissions de NO_x lorsque la température du lit croissait, alors que dans le cas des deux autres fournaises, aucune corrélation n'a été constatée. Dans le cas de deux des fournaises pilotes seulement, les émissions

de NO_x se sont augmentées en présence d'un excès d'oxygène. Il semble qu'il n'y ait aucune corrélation entre les émissions de NO_x et l'excès d'oxygène dans le cas des trois autres fournaise pilotes. Les émissions de NO_x observées à la fournaise industrielle de chauffage sont nettement plus importantes que celles que l'on a observées dans les cinq fournaises pilotes, probablement parce que la fournaise de chauffage utilise des taux anormalement élevés d'excès d'oxygène, ce qui produit en conséquence des taux anormalement bas de CO. Toutefois, dans cette fournaise, les émissions de NO_x diminuent légèrement lorsque l'excès d'oxygène est en augmentation, probablement parce que l'augmentation de la circulation d'air favorise la décantation des poussières de charbon, et il en résulte des taux un peu plus élevés de CO dans le franc-bord.

Une étude de l'effet du rapport molaire Ca/S indique qu'il existe une forte corrélation entre l'augmentation de l'émission de NO_x et l'augmentation du rapport molaire Ca/S pour l'une des fournaises à lit fluidisé circulant. Il semble y avoir peu de corrélation dans le cas des cinq autres fournaises étudiées. Toutefois, on a observé une diminution de l'émission de NO_x avec le rapport molaire Ca/S dans quelques programmes de test.

1. INTRODUCTION

Fluidized bed combustion (FBC) is recognized as one of the most promising technologies for controlling both SO_2 and NO_x emissions from coal-fired industrial plants.

The development and application of FBC technology has been supported by Energy, Mines and Resources Canada via its Combustion and Carbonization Research Laboratory (CCRL) in the Canada Centre for Mineral and Energy Technology (CANMET). Since the seventies, a wide variety of Canadian fuels, and one American coal (Kentucky No. 9) have been tested in several pilot and industrial scale fluidized bed combustors, including both bubbling and circulating types. As a result, a large body of data on the combustion performance of these fuels has accumulated.

This report is devoted to the summary, comparison, evaluation and assessment of SO_2 and NO_x emissions in FBC based on this body of data. The work was supported by contract No. 007SQ-23440-8-9213 under the auspices of the Canada Centre for Mineral and Energy Technology (CANMET), Energy, Mines and Resources Canada. The contract commissioned a critical scientific review and analysis of existing data in order to provide:

(a) a review of typical SO_2 and NO_x emissions levels from FBC systems;

(b) correlation of SO_2 and NO_x emissions to fuel and operating parameters; and

(c) an assessment of how best to minimize SO_2 and NO_x emissions from FBC systems.

Detailed requirements of the contract are outlined in the statement of the work, see Appendix E.

2. TEST INFORMATION

2.1 THE TEST PROGRAMS

The data summarized in this report are collected from twenty one technical reports for a series of investigations in which Canadian candidate fuels were burned by atmospheric fluidized bed combustion during the period 1980 to 1987 [1-21]. These tests were conducted in five pilot-scale combustors consisting of three atmospheric bubbling fluidized bed units and two atmospheric circulating fluidized bed units.

This report also incorporates data collected during acceptance tests and demonstration trials conducted at Canada's first bubbling fluidized bed heating plant located at Summerside, Prince Edward Island. These trials were conducted to evaluate the capacity of the fluidized bed boiler to perform at different loads within the environmental guidelines using a variety of coals available locally.

Also included are results of three tests carried out for the U.S. Environmental Protection Agency (EPA) at the Summerside plant as follows: (1) a 30-day continuous test with full load and the requirement of a 90% or greater sulphur reduction, (2) an 8-hour test with part load using limestone of large size to achieve the same sulphur capture, and (3) a 20-hour test for maximum sulphur retention.

Information on the type of fuel, facility used, number

of runs conducted and source report of the 40 test programs used in this report is given in Table 1. The test programs are grouped according to fuel used.

2.2 THE FUELS

The fuels tested include twelve types of coal, ranking from lignite through bituminous coal to anthracite, a coal washery reject, three by-product cokes from petroleum refinery processes, four heavy liquid fuels and a coal/water slurry.

Five of these coals (Minto, Devco, Evans, Brogan and Novaco) are Eastern Canadian coals. Typically, these coals are high in sulphur and have the additional drawbacks of high ash contents and low ash fusion temperatures. Therefore, they are good candidate fuels for fluidized bed combustion. Also included in the tests are six low-sulphur coals, Onakawana lignite from south of James Bay, Highvale sub-bituminous from central Alberta and four coals from British Columbia. For comparison, the results of trials with one American coal, referred to as Appalachian or Kentucky No.9, are also included. As alternative fuels, results of tests on a washery reject from Devco coal and three by-product cokes from petroleum refinery processes are included. Two of the by-product cokes are residues of oil-sand extraction at the Syncrude and Suncor plants, located at Fort McMurry, Alberta. The third is the product of a delayed coking process at the

Consumers Co-op Refinery at Regina, Saskatchewan. The cokes are low in volatiles with sulphur contents which are moderate for the Saskatchewan coke to high for the Syncrude and Suncor cokes.

Data from tests on liquid fuels consisting of bitumen and pitches from an heavy oil upgrading process, and a #6 oil are included. These fuels have a moderate sulphur content and sometimes contain heavy metals. These liquid fuels have high heating values. Also included are the results of tests of a coal/water slurry prepared by the Cape Breton Development Corporation employing Devco bituminous as the parent coal.

The averaged values of chemical analysis for these fuels are provided in Table 2. Values are given for the mass percentage for elements and ash, proximate analysis for volatile matter (VM), fixed carbon (FC), moisture (MOIS), and high heating value of each fuel (HHV). All values are given on a dry basis except for moisture. The properties of a specific fuel vary slightly from batch to batch and may be different for trials with the same fuel when delivered in different shipments. Exact results of the chemical analyses for fuels used in a specific test program may be found in the source report for the particular test.

2.3 THE FACILITIES

The facilities used for the test programs include three

pilot-scale atmospheric bubbling fluidized bed combustors, an industrial bubbling fluidized bed heating plant and two pilot-scale circulating fluidized bed combustors.

Modifications were made to the fuel feeding systems to ensure successful trials when liquid fuels were tested [6, 14]. However, this did not alter the main configuration of the facilities used.

2.3.1 Pilot-Scale Bubbling Fluidized Bed Combustors

A small pilot-scale fluidized bed combustor (Mark I) was erected in 1975 at CCRL and was used to perform the early test programs. The facility (Fig. 1) consisted of a combustor which had an inside diameter of 240 mm and stood about 2.9 m high, a fuel hopper placed on an electronic scale and a cyclone to collect elutriated solids. A detailed description can be found elsewhere [7-10]. This combustor was distinct in that it was cooled by injection of water into the bed.

The other two pilot-scale bubbling fluidized bed combustors are essentially identical. One is located at CCRL (Mark II) and the second at Queen's University. These two combustors are described in detail elsewhere [1, 2, 22].

The schematic diagram of the combustor Mark II is shown in Fig. 2. The combustor is 4.8 m high and has internal dimensions of 380X406 mm giving a bed area of 0.155 m^2. The combustor is equipped with a fuel hopper, a sorbent hopper, a multicyclone dust collector with means for fly ash recycle,

a gas-to-air heat exchanger downstream of the dust collector, a baghouse and a stack. The hoppers sit on electronic weigh scales and the fuel and limestone are screw fed into the bed either by an over-bed port or an under-bed port. Although there is a facility to accommodate up to 48 in-bed water cooling tubes, in practice no more than twenty four were used.

The combustor is also equipped with instrumentation including infrared analyzers for on-line measurements of CO, CO_2 and SO_2; an ultraviolet analyzer for SO_2; a paramagnetic analyzer for O_2 and a chemiluminescent NO_x analyzer. All data are logged to an automatic data acquisition and control system and stored on computer disk every 5 minutes. An electronic data logger also records all the data as a backup.

The major difference between the pilot-scale bubbling fluidized bed combustor at Queen's University and that at CCRL is a bed overflow port located 1.19 m above the distributor plate in the Queen's University combustor. In the CCRL combustor, the spent bed material is drawn from a drain near the base of the bed. The freeboard zone of the combustor at Queen's University extends to about 423 cm above the distribution plate, which is about 93 cm higher than that of the combustor at CCRL. The freeboard of the combustor at CCRL is uncooled while the freeboard of the combustor at Queen's University was equipped with heat exchange tubes at the top with a waterwall extension in place for some of the tests.

2.3.2 Industrial Bubbling Fluidized Bed Heating Plant

The industrial bubbling fluidized bed heating plant located at Summerside, Prince Edward Island has two identical natural circulation boilers each rated at 18,000 kg/h of steam. One of the boilers was used to generate the test data used in this work. The detailed structure of the boilers is provided in the report prepared by Monenco Consultants Ltd. [23].

The furnace in each boiler is divided by a membrane-tube wall into two sections designated as the preferential bed and secondary bed, Fig. 3. The internal cross sectional dimensions of the two beds are 1.22X2.90 m and 1.37X2.90 m, respectively. Both beds are surrounded by membrane walls. However, only the secondary bed has an immersed heat transfer surface in the form of 18 inclined tubes passing through it. A multi-cyclone is used to capture the elutriated particles. All solids collected in the cyclone and the convective tube bank are recycled to the preferential bed only. Only the preferential bed was in operation when tests with minimum load were carried out.

The instrumentation for the flue gas analysis and data acquisition system for the tests conducted at this heating plant were identical to those installed at the pilot plant at CCRL.

2.3.3 Pilot-Scale Circulating Fluidized Bed Combustors

One of the two circulating fluidized bed combustors is located at The University of British Columbia. The facility includes a combustor, two hoppers, two cyclones, a heat exchanger and a baghouse, as shown in Fig. 4. Further details may be obtained from the UBC report [19].

The reactor chamber has an internal cross sectional area of 152X152 mm (6 inches square) and an overall height of 7.32 m (24 feet). The heat is removed by a membrane waterwall heat transfer surface constructed on one wall of the column 4.27 m above the distributor plate. The solids are fed to the bed from the hoppers via rotary valves by a screw feeder. The solids, separated in a primary cyclone, descend in a moving packed bed flow in a vertical leg and return to the bed. The solids captured in the secondary cyclone are collected in a receiving vessel. Gas leaving the secondary cyclone is cooled in a U-tube heat exchanger and then discharged to the ventilation system.

The combustor is equipped with instrumentation for analysis of the flue gas. This includes on-line analyzers for measuring the concentrations of O_2, SO_2, NO and NO_2. During the tests, samples were also collected with a syringe for injection into a gas chromatograph for analysis of CO, CO_2 and confirmatory readings of the SO_2 concentration. All the data are collected by a data acquisition system and stored on disk.

The second atmospheric circulating fluidized bed facility, the PYROFLOW pilot plant of the Ahlstrom Corporation, is located in Karhula, Finland. The features of the combustor are described in the report of Polymath Energy Consultants Ltd., Ahlstrom Corporation and Pyropower Corporation [20].

The combustor is 8.5 m high with an internal diameter of 600 mm, and is shown in Fig. 5. Solid fuel and limestone are fed from two adjacent feed hoppers via screw conveyers and rotary valves into a loop seal ash return flow to the combustor. Heat is removed and the temperature is partially controlled by the use of water-cooled bayonet coolers inserted into the top of the combustion chamber. Gases and bed materials leaving the combustor are separated in a cyclone. The cyclone is approximately the same diameter as the combustor (600 mm) and approximately 3 m high. At the base of the cyclone a vertical tube delivers solid material to a non-mechanical loop seal which transfers solids back into the combustor. Gases exiting the cyclone are cooled to about 200 C through a gas/water heat exchanger and then enter a two-compartment baghouse with air pulse cleaning to remove fine particulate matter. The ash is collected in a hopper in the base of the baghouse and may be directed to a bin below the baghouse or into a screw feeder and rotary valve for pneumatic transport back to the combustor. All gas flow eventually enters a vertical venturi scrubber prior to the

induced draft fan and stack.

Test instrumentation on the combustor includes: Westinghouse and Taylor excess O_2 analyzers; Teco CO analyzer; Teco, Uras and Monitor Labs SO_2 analyzers; Beckman and Monitor Labs NO_x analyzers; J.U.M. total hydrocarbon analyzer; Severn Science SO_3 analyzer and Isokinetic particulate sampler.

3. THE DATA

The experimental data collected in each test program were reviewed and summarized. The results are presented in Tables 3 and 4. In these two tables, the data for each test program from each fuel using each facility is listed in separate blocks. Details of the fuel tested, the facility used and the source report are indicated at the beginning of each data block. Data blocks are arranged in the same order as the summary of the test programs in Table 1.

In Tables 3 and 4, the operating conditions are summarized in terms of bed temperature, calcium to sulphur molar ratio (Ca/S), excess oxygen level and fuel firing rate. The fuel firing rates have been converted to units of MJ/m^2h as required in the contract. The excess oxygen level is calculated from the total flow rate of the air used and a theoretically determined stoichiometric air level. The calculation procedure for determining the stoichiometric air and the excess oxygen levels are given in Appendix A. The data for total flow rate of the air are usually available in the reports accessed. However, for the tests conducted with Devco coal at CCRL (serial number 8 in Table 1) and some of the tests performed at UBC (serial numbers 4, 36 and 38 in Table 1), the total air flow is calculated from the superficial velocity given in the reports. For the remainder of the tests conducted at UBC (serial numbers 5, 20, 23, 26, 37 and 39), the total air flow is determined from the excess

air level given in the report and the stoichiometric air flow calculated from the fuel firing rate.

The Ca/S molar ratio provided in Table 3 is the molar ratio of calcium added to the combustor as sorbent to the sulphur contained in the fuel. In some of the source reports, the Ca/S ratio is defined as the molar ratio of total calcium including both the calcium in the ash and the limestone added to the sulphur contained in the fuel [8, 15]. For these reports the Ca/S molar ratio listed in the tables is re-calculated from the limestone and fuel feed rates.

Emission data given in the tables include the concentrations of SO_2, NO_x and CO in the flue gas. The emission data for NO_x and SO_2 are given in units of ng/MJ as well as $lb/10^6$ Btu. The NO_x values are also presented in terms of percentage of fuel nitrogen converted to NO_x. These data are determined from calculated flow rates of dry flue gas. The procedures for these calculations are outlined in Appendix A.

The tables also include the measured concentration of O_2 in the flue gas. This information provides a measure of the excess oxygen level and is readily available for most of the tests.

Where possible, mean values and standard deviations are provided for bed temperature, fuel firing rate, SO_2 emission, NO_x emission and CO emission. Unfortunately, the standard deviations are not listed for many of the tests since the

reports accessed do not contain this information.

In some of the reports, primarily the reports from Queen's University, the reports presented data in graphic rather than numeric form. In order to obtain numeric data from these tests, we have accessed the original computer disks or laboratory notes containing the records of the tests. Reduced data from these records are presented in our summary. A careful examination shows an excellent agreement between the reports and the regenerated data.

For the acceptance and the demonstration tests carried out at the industrial heating plant at Summerside, information was extracted directly from computer reduced experimental data supplied by CANMET [17] since there is no formal report available.

For the three U.S. EPA tests, detailed computer reduced data are not available. The data given in the tables of this report are obtained from the report prepared by Radian Corporation [18]. The emission data of SO_2 and NO_x are given as $lb/10^6$ Btu in the source report. Information on the total air flow is not available making it impossible to calculate the excess oxygen level for these tests.

4. EVALUATION OF SO_2 EMISSION

4.1 INTRODUCTION

SO_2 emission data were examined for the following correlations:

-SO_2 to Ca/S molar ratio;

-SO_2 to fuel type;

-SO_2 to bed temperature;

-SO_2 to excess O_2 level;

-SO_2 to CO level in the flue gas;

-SO_2 to NO_x emission; and

-SO_2 to facility.

The results on the effect of the most influential factor, the amount of limestone added, are presented in Section 4.2 followed by the results on the effects of fuel type and bed temperature in Sections 4.3 and 4.4. The effects of excess O_2, and relationship to CO and NO_x emission levels are found to be relatively insignificant and closely correlated with each other. These factors are discussed in Section 4.5. Section 4.6 is devoted to the effect of the facility. Comparisons are made in this section between the results of pilot-scale tests and full-scale tests, and the results of bubbling FBC tests and circulating FBC tests. A discussion of models for the correlation between SO_2 emission and the operating parameters is given in Section 4.7.

In order to relate results from coals with different

sulphur content, we will define a standardized SO_2 emission E_1 as

$$E_1 = E_{10}/W_1, \qquad (4.1.01)$$

where E_{10} is emission of SO_2 in ng/J and W_1 is the sulphur content of the fuel in ng/J. As will be discussed in Section 4.3, SO_2 emission is proportional to the sulphur content of the fuel. Thus the quantity E_1 will not vary significantly with fuel type. In order to eliminate the effect caused by the difference in fuel type, the values of E_1 will be used in later discussions where more than one fuel is involved.

4.2 EFFECT OF Ca/S MOLAR RATIO ON SO_2 EMISSION

Addition of sorbent significantly reduces SO_2 emission due to the calcination and sulphation reactions:

$$CaCO_3 \text{ --> } CaO + CO_2 \qquad (4.2.01)$$

and

$$CaO + (1/2)O_2 + SO_2 \text{ <--> } CaSO_4. \qquad (4.2.02)$$

It offsets effects of other operating parameters such as excess oxygen level, bed temperature, fuel firing rate, CO and NO_x emission levels. This phenomenon is most clearly shown in the tests with fuels having low calcium content, e.g., Minto and Devco coals. A typical example is shown in Fig. 6 where the SO_2 emission is plotted against the bed temperature. In this figure the SO_2 emission data points are separated into two distinct regions. SO_2 emission for the base line tests all occur at approximately the 4000 ng/J

region. With addition of limestone the emission always falls to below 2000 ng/J with an average of about 1000 ng/J. More examples are given in Appendix B, Figs. B101, B301, B401, B501, B102, B202, B302, B402 and B502.

The effect of the sorbent is further illustrated by the results from the tests with extensive limestone addition, Table 5 and Figs. 7-12. These results are from 26 test programs in which eleven fuels including four liquid fuels, one American coal and one petroleum coke were tested. Three high-sulphur Eastern Canadian coals, Minto, Devco and Evans, and the Syncrude coke have been tested most extensively. Information on the fuels, and the number of runs conducted in combustors of each type are provided in Table 5.

The results of the analysis indicate a consistent decrease of SO_2 emission with increasing addition of limestone. This is clearly shown in Figs. 7-12, in which the Ca/S molar ratio is plotted against the SO_2 emission. For a given value of the Ca/S molar ratio, the amount of calcium actually added depends on the fuel feeding rate and the sulphur content of the fuel. To avoid the effect of fuel type, the standardized SO_2 emission E_1 defined by Eq. 4.1.01 is used.

It is evident from Fig. 7 that more effective reduction of SO_2 emission by calcium is obtained when a smaller size of in-bed limestone particles is used. Fig. 7 plots the variation of SO_2 emission of Minto coal with Ca/S molar

ratio, the highest emission is observed in the tests at Queen's University when large size limestone (1.72-1.98 mm) is employed. The emission of SO_2 observed in the tests conducted in the same combustor with limestone of 0.49-1.11 mm is much lower. The SO_2 emission observed in these tests agrees well with the results obtained in the tests conducted in the bubbling FBC combustor, Mark I, using limestone with an average size of 1.1 mm and the tests conducted in the circulating FBC combustor at UBC using limestone of 0.21-0.45 mm.

Figure 7 also shows that the emission of SO_2 from the Summerside heating plant is in approximately the same range as that observed in the pilot-plant tests with a limestone size of 0.49-1.1 mm. The limestone fed in the Summerside plant is relatively coarse, 0.85-2.36 mm. However, the size of the in-bed limestone particles in this plant is reduced significantly due to a strong grinding effect of the bed material caused by the relatively high velocity employed, approximately 2.5-4.5 m/s compared to 1.6-2.9 m/s at Queen's University and 1.3-3.8 m/s in Mark I. Analysis of bed material shows that the average size of the in-bed limestone particles for the tests conducted at the Summerside heating plant is approximately 0.85-1.18 mm [17], which is close to the size of the limestone employed in the pilot plant tests.

Figure 8 shows the effect of Ca/S molar ratio on the emission of SO_2 for Devco coal. The results of the tests with

the washery reject from Devco coal are also included since the physical and chemical properties of the washery reject are similar to those of the parent coal. The size of the limestone used in these tests covers a much wider range, 0-6.3 mm. This wider range may account for the greater scatter of the measurements.

Figure 8 also provides evidence of the stronger effect of the Ca/S molar ratio on SO_2 emission when a recycle system is in operation. This is especially true in the tests where limestone fines are used. In the tests with 0-6.3 mm limestone, which contains fine particles, the SO_2 emission is much lower when the recycle system is on. The recycle system reduces the mean size of the in-bed limestone particles and provides longer residence times for fine sorbents by returning the elutriated limestone fines to the bed and thus enhancing sulphur capture.

The effect of limestone size on SO_2 emission may be explained via a surface effect on the sulphation reaction Eq. 4.2.02 occurring in the combustor. Usually the CaO does not completely convert to $CaSO_4$ because the product of the sulphation reaction, $CaSO_4$, deposits on the walls of the pores of the CaO particle preventing the O_2 and SO_2 gases from reaching the interior of the particle [24]. Limestone particles of smaller size provide larger internal surface available to the reaction [25] The conversion to $CaSO_4$ for these particles is thus more complete. The experiments show

that the apparent reactivity of the limestone decreases with the size of the particles [26]. This explains the reduction of SO_2 emission as the limestone size is reduced.

Figures 9-12 give further evidence of the strong correlation between Ca/S molar ratio and SO_2 emission observed in tests using different facilities. Figs. 9 and 10 show the results obtained in the tests conducted at the Summerside heating plant and the pilot-scale plants including the bubbling FBC combustors Mark I, Mark II and that at Queen's University. In Figs. 11 and 12 the results from the tests with Syncrude coke and CANMET pitch conducted at both bubbling and circulating FBC pilot plants are presented.

4.3 EFFECT OF FUEL TYPE

Since addition of sorbent ($CaCO_3$) significantly offsets the effect of fuel type on SO_2 emission, only the results from base line tests, i.e. those tests without addition of sorbent, are used to analyze the effect of fuel type. For these tests, information on fuel type, facility used, number of runs conducted, calcium content of the fuel and the SO_2 emission observed are given in Table 6. Results of the tests with sixteen fuels, including eight different coals, three petroleum cokes, a washery reject and four liquid fuels are included. Both bubbling FBC results and circulating FBC results are available. The emission data provided in this table are average values of all runs performed in each test

program.

Some of the fuels, i.e. Highvale coal and Poplar River lignite, contain relatively high calcium. Thus, the base line tests with these fuels cannot be considered as sorbent free tests. After excluding these tests, the emission data are well correlated to the sulphur content of the fuel as shown in Fig. 13. Considering that the emission of SO_2 should be zero if the fuel contains no sulphur, statistic analysis gives a best representation of the correlation between the emission of SO_2 and the fuel sulphur as:

$$E_{10} = (1.43 \pm 0.06) * W_1 \qquad (4.3.01)$$

where E_{10} is the emission of SO_2 in ng/J and W_1 is the sulphur content of the fuel, also in ng/J.

Since the molecular weight of SO_2 is twice that of sulphur, E_{10} should be equal to $2*W_1$ if all the sulphur is emitted as SO_2. The ratio of 1.43 between the emission of SO_2 observed in the base line tests and the fuel sulphur indicates that about 28.5% sulphur is lost through solid combustion products. In order to meet the federal guideline of 258 ng/J for SO_2 emission, therefore, no sorbent addition is required for fuels with sulphur content less than about 184 ng/J. However, some fuels with sulphur content between 184 ng/J and 500 ng/J, due to sulphur capture by ash constituents, may also be included in this category. From the results shown in Table 6, these fuels are Byron Creek, Line Creek, Highvale and Mt Klappan coals, and Poplar River

lignite. For those fuels with sulphur content higher than 500 ng/J, addition of sorbent is necessary.

4.4 EFFECT OF BED TEMPERATURE

The sulphation reaction Eq. 4.2.02 is exothermic and reversible. The bed temperature has a direct effect on the rate constants of the forward and reverse reactions and thus on the equilibrium position of the reaction. The bed temperature therefore influences the amount of sulphur captured.

Examination of the data body indicates that SO_2 emission varies only slightly or does not change with the bed temperature in those base line tests of fuels with a low calcium content. This is due to insignificant sulphation reaction occurring in the combustor. This includes the base line tests with Minto coal, Devco coal, Suncor coke, the coal/water slurry prepared from Devco coal and the Saskatchewan petroleum coke. A typical example is shown in Fig. 6 where the results of Minto coal tests are presented. More examples are provided in Figs. B202 and B210 in Appendix B.

In most base line tests, for fuels containing a large calcium content, i.e., where the Ca/S molar ratio is above approximately 0.2, the emission of SO_2 observed in the base line tests increases with bed temperature. This includes the tests with Line Creek coal and Onakawana lignite, and most

of the runs with Highvale and Mt Klappan coals as shown in Figs. 14-16. The effect of bed temperature is relatively flat except for the tests with Mt Klappan coal where a sharp increase of SO_2 emission is observed when the bed temperature exceeds approximately 920 deg. C (Fig. 16). Byron Creek coal appears to behave quite differently in that the bed temperature does not appear to have an effect on the SO_2 emission in the range of 800-1000 deg. C (Fig. 14).

There is some evidence to indicate that the effect of bed temperature on SO_2 emission may differ with the facility used. As shown in Fig. 14, the SO_2 emission does not vary with the bed temperature when Highvale coal is tested in the circulating FBC at UBC, increases only slightly with the bed temperature in the tests conducted at Queen's University, but increases significantly when the fuel is tested in the FBC Mark I.

For tests with addition of limestone, the effect of bed temperature appears to be much less important than the Ca/S molar ratio if the bed temperature varies only in the usual temperature range for a FBC system, i.e. 800-900 deg. C, as is the case in most of the tests summarized in this work. Typical examples are the tests using Minto and Devco coal with extensive addition of limestone, e.g., Fig. 6 and Fig. B202 in Appendix B. However, over a wider temperature range, the effect of bed temperature may become the dominant factor for sulphur capture as shown in the bubbling pilot-plant

tests with Syncrude coke, Fig. 17. It should be noted, however, that the Ca/S molar ratio is varied only moderately in the tests shown in this figure. For the tests conducted in the Mark II combustor, the Ca/S molar ratio varies from 1.12 to 4.68, for the tests at Queen's University, the Ca/S molar ratio varies between 1.73 and 3.38. The SO_2 emission is consistent with that observed in the normal temperature range, around 850 deg. C. With increasing bed temperature, the emission of SO_2 increases but remains low to about 1050 deg. C as shown in this figure. It then rises very sharply, to practically no sulphur capture beyond 1100 deg. C.

The effect of bed temperature on SO_2 emission is also evident in the tests at the Summerside heating plant as shown in Fig. 18. The results of CANMET tests conducted at this plant with five coals are consistent with each other. The SO_2 emission remains low and unchanged in the range of 840-870 deg. C, a typical temperature range for a FBC system. It then increases when the bed temperature decreases from the normal level. The SO_2 emission observed in the US EPA tests is significantly lower than that observed in CANMET tests due to much larger Ca/S molar ratio (3.7-7.2) employed in these tests compared to the CANMET tests where Ca/S values were between 0.7 and 3.5. Therefore, it is not unexpected that the US EPA and CANMET tests would give differing results.

4.5 EFFECT OF OTHER PARAMETERS

Also examined are the effects of excess oxygen, the fuel firing rate, and the relationship to CO emission and NO_x emission. With few exceptions, we could identify no noticeable trend for SO_2 emission with these parameters in the pilot-plant tests, see Appendix B. The exceptions include the tests of Byron Creek and Line Creek coals where standardized SO_2 emission is found to increase with excess oxygen, Fig. 19, and to decrease with CO emission, Fig. 20. The SO_2 emission observed in the tests with Onakawana lignite also increases with the excess oxygen as shown in Fig. 21.

However, the standardized emission of SO_2 in the CANMET tests conducted at the Summerside heating plant shows consistent trends with these parameters. It increases with increasing excess oxygen, Fig. 22, and CO emission, Fig. 23, and decreases with increasing fuel firing rate, Fig. 24, and NO_x emission, Fig. 25. The results of the US EPA tests are not consistent with the CANMET tests due to the much higher Ca/S ratio employed.

Examination further shows that the trends for SO_2 emission with these operating parameters observed at the Summerside heating plant are interrelated. The bed temperature decreases with the excess oxygen due to dilution of the combustion mixture, as shown in Fig. 26. The SO_2 emission is thus reduced by the excess air due to the resulting reduction in bed temperature. In other words, the increase of SO_2 emission with excess oxygen as shown in Fig.

22 is consistent with the increase of SO_2 emission with decreasing bed temperature as shown in Fig. 18. Similarly, the bed temperature increases with fuel firing rate which leads to a decrease of SO_2 emission with the firing rate as shown in Fig. 24.

These effects attributed above to excess oxygen may in fact be the result of a reduction of gas residence time in the bed and freeboard and an enhanced loss of sorbent fines from elutriation as a consequence of the high air flow rates.

An unique feature of the Summerside heating plant is the tendency of SO_2 emission to decrease with decreasing CO emission and increasing NO_x emission as indicated in Figs. 23 and 25. This is consistent with the increase of SO_2 emission with excess oxygen since CO emission increases with excess oxygen due to the enhanced elutriation of char fines resulting in a decrease of NO_x emission. The effect of excess oxygen on CO and NO_x emissions will be further discussed in Section 5.8.

4.6 DEPENDENCE OF SO_2 EMISSION ON FACILITY

The significant dependence of SO_2 emission on facility observed in the tests with extensive addition of limestone is not evident in calcium-free tests where the average SO_2 emission varies only with sulphur content of the fuel as indicated in Fig. 13. The dependence of SO_2 emission on facility therefore appears to be related to the calcination

and sulphation reactions Eqs. 4.2.01 and 4.2.02.

Figure 9 compares the results from the full-scale bubbling FBC plant at Summerside with representative curves (A and B) for both pilot-scale and full-scale bubbling FBC plants, calculated according to models discussed in Section 4.7. It is obvious that the emission of SO_2 observed at the Summerside heating plant can be predicted by the results of the tests conducted at the pilot plants with a fairly good accuracy. The operating parameters employed in the bubbling pilot-plant tests vary over a wide range. The limestone used in these tests was sized from zero to 6.3 mm. The data for SO_2 emission, on which the statistic models are based, scatter considerably, as shown in Fig. 10. It should be noted that pilot-plant tests are not available for some of the coals tested at the Summerside heating plant, e.g., Brogan and Novaco. Taking these factors into account, the results of the bubbling pilot-plant tests should be considered to agree very well with the tests conducted at the Summerside heating plant.

The results of the tests with Minto coal, which are the only results with extensive addition of limestone available for both bubbling and circulating FBC, indicate that the SO_2 emission observed in the circulating FBC tests is approximately of the same magnitude as that in the bubbling FBC tests as shown in Fig. 7. The SO_2 emission observed in these tests is expected to be lower than the bubbling FBC

tests because of the smaller size of the limestone employed, 0.21-0.45 mm. A circulating FBC allows limestone of a much smaller size to be used and thus to achieve a more efficient sulphur capture.

As mentioned in Section 4.5, an unique correlation observed at the Summerside heating plant is the decrease of SO_2 emission with increasing NO_x emission and decreasing CO emission. This effect is not found in the bubbling FBC pilot plant. However, it is not clear if the unusually high excess oxygen level employed or the large scale of the unit is responsible for this behaviour.

Tests on Syncrude coke provide evidence that the SO_2 emission is much lower in a circulating FBC than in a bubbling FBC as shown in Fig. 11. Since we found that bed temperature becomes a significant factor above 1050 deg. C, we have excluded the results above 1050 deg. C for this comparison.

The different efficiency in sulphur capture observed in these two types of FBC systems results from their different structure. The active zone for a bubbling FBC system which includes the bed and the splash zone is relatively short, typically about 1-3 m for a pilot-scale combustor. Only a small fraction of the fuel sulphur is captured beyond the active zone, i.e. the free board [27]. Because of the small size of the Syncrude coke, a mean surface size of the fuel is 0.15 mm and typically 98% of the material is less than 0.5 mm

while 67% is less than 0.25 mm, the fuel particles are easily elutriated in bubbling FBC systems. The efficiency in sulphur capture is reduced since some of SO_2 gas is generated in the freeboard and escapes without contact with the limestone.

Unlike the bubbling FBC systems, circulating FBC systems allow fine particles to be used as bed material, typically 0.05-0.5 mm in mean size compared with 1-3 mm for a bubbling FBC system, and a considerably higher superficial velocity to be employed, typically 5-10 m/s as compared with 1-3 m/s for bubbling FBC systems. The particles carried over from the combustion chamber are returned to the base of the reactor continuously. The SO_2 gas generated in the combustion of the fuel is thus able to come into contact with the sorbent particles throughout the entire combustion chamber. The efficiency of sulphur capture is therefore enhanced.

A better efficiency in sulphur capture of the circulating FBC system is also evident in tests with liquid fuels. It is clearly shown in Fig. 12, that the Ca/S molar ratio required for the same sulphur capture is doubled when the CANMET pitch is tested in the bubbling FBC Mark II compared to that in the tests at the UBC circulating FBC plant.

As expected, most liquid fuels like heavy oil or pitches devolatilize quickly after entering the combustor and burn mainly as volatiles with little solid residue left for consequent combustion [14]. The contact time of the SO_2 gas

generated in the combustion of the volatiles is expected to be much longer if a liquid fuel burns in a circulating FBC plant compared to that in a bubbling FBC plant. The emission of SO_2 is therefore considerably lower when the liquid fuel is tested in a circulating FBC system.

As mentioned in Section 4.4, a weak dependency of SO_2 emission on facility among bubbling FBC plants is also evident. A typical example is the effect of temperature found in tests with Highvale coal as shown in Fig. 14. Processes related to the sulphation reaction occurring in the freeboard are likely to be responsible for such an apparatus dependency of the effect of bed temperature on the emission of SO_2. These include: burning of char, producing SO_2; capture of SO_2 by the elutriated CaO fines; decomposition of $CaSO_4$, producing SO_2; and adsorption or desorption of SO_2 by fine solid particles. For bubbling FBC systems, the height and the temperature of the freeboard may vary significantly from unit to unit. As a result, SO_2 emission may depend slightly depends on facility even among bubbling FBC plants.

4.7 EMPIRICAL MODELS FOR SO_2 EMISSION

4.7.1 Previous Empirical Models

Several nonlinear models have been proposed to predict the fraction of sulphur retained based on the operating parameters, and in particular the key parameter, the Ca/S

molar ratio. In these models, the fraction of the fuel sulphur captured, S_r, is used as the dependent variable instead of the emission of SO_2. The relationship between these two variables is

$$E_{10} = 2*(1 - S_r)*W_1 \qquad (4.7.01)$$

It has been found that the fraction of fuel sulphur captured is well correlated to the Ca/S molar ratio employed by an exponential function [28-31]. In previous work, two models were proposed [28, 29]:

$$S_r = 1 - \exp[-B_1*(Ca/S)] \qquad (4.7.02)$$

and

$$Ln\ [1 - S_r] = -B_1*(Ca/S)*\exp[-B_2/(T_b + 273)], \qquad (4.7.03)$$

where B_1 and B_2 are coefficients of the models. Equation 4.7.03 is rarely used by other investigators. In addition, this model has been found to be inappropriate in fitting the data of the US EPA tests conducted at the industrial heating plant at Summerside [18]. This model is therefore excluded from consideration in the present work.

Equation 4.7.02 has been used to predict the emission of SO_2 from Minto coal successfully [10]. In order to improve the model, another coefficient has been introduced in more recent investigations [12, 30] and the model becomes

$$S_r = 1 - \exp[(B_2*(Ca/S) - B_1)*(Ca/S)]. \qquad (4.7.04)$$

This model has been applied to some of the tests with Devco coal and the tests conducted at Summerside heating plant [12, 30]. The resulting models are:

$$S_r = 1 - \exp[(0.049*(Ca/S) - 0.987)*(Ca/S)], \quad (4.7.05)$$

$$S_r = 1 - \exp[(0.054*(Ca/S) - 0.447)*(Ca/S)] \quad (4.7.06)$$

and

$$S_r = 1 - \exp[(0.033*(Ca/S) - 0.447)*(Ca/S)]. \quad (4.7.07)$$

An attempt to include the effect of operating parameters other than the Ca/S molar ratio into the model has also been made. A typical resulting model is [31]

$$S_r = 1 - \exp[-0.690 - (0.071/V)*(Ca/S)] \quad (4.7.08)$$

where V is the superficial velocity.

Examination indicates that the basic form of these empirical models is Eq. 4.7.02 which is simple and yet reflects the effect of the most influential factor, the Ca/S molar ratio. This model, therefore, is effective in predicting SO_2 emission, however, the effects of operating parameters other than Ca/S are not included in this model. A more serious problem of the model is that it predicts an 100% sulphur emission for base line tests and thus does not agree with experiments. As mentioned previously only about 72.5% of the fuel sulphur is emitted in base line tests. Since the effect of fuel sulphur usually is significant, an appropriate empirical model should be able to reflect this effect properly.

In Eq. 4.7.04, the second coefficient and the term $(Ca/S)^2$ are introduced, providing a better fit to test data [12]. This model also fails since it does not predict the correct values for SO_2 emission in base line tests.

In Eq. 4.7.08, yet another coefficient is introduced to improve the fit. Unlike Eq. 4.7.04 this model provides a better prediction for base line tests. In this model the superficial velocity is separated from other operating parameters and treated as an independent variable of the same order as the Ca/S molar ratio. This is not valid since, according to our analysis, the superficial velocity is less important than the Ca/S molar ratio in its effect on SO_2 emission.

We may conclude from the foregoing discussion that an exponential function appears to be the most suitable form to correlate SO_2 emission to operating parameters. The most influential factor, the Ca/S molar ratio, may be used as the only independent variable to simplify the correlation while incorporating the effects of other influential factors into coefficients that are properly set in the model. The effect of fuel sulphur on SO_2 emission is also an important factor. This effect has to be, and can be well reflected in the model. The effect of the other operating parameters is of secondary importance. These parameters should not be treated as equal in importance to the Ca/S molar ratio or the fuel sulphur. To incorporate these parameters into one coefficient appears to be appropriate for a simple empirical model.

4.7.2 The Proposed Model

From the present analysis we propose as an empirical

model

$$S_r = 1 - B_2*\exp[-B_1*(Ca/S)] \qquad (4.7.09)$$

where the Ca/S molar ratio is the only independent variable, and B_2 is the coefficient reflecting the effect of the fuel sulphur. The effect of the other operating parameters is incorporated in the coefficient B_1. Expressing the emission of SO_2 as E_{10}, the correlation has the form

$$E_{10} = 2*B_2*W_1*\exp[-B_1*(Ca/S)], \qquad (4.7.10)$$

By using the general relationship between fuel sulphur and the emission of SO_2 in base line tests, Eq. 4.3.01, an alternative expression for Eq. 4.7.10 is

$$E_{10} = 1.43*W_1*\exp[-B_1*(Ca/S)] \qquad (4.7.11)$$

Expressed as a standardized emission E_1, the expressions become

$$E_1 = 2*B_2*\exp[-B_1*(Ca/S)], \qquad (4.7.12)$$

and

$$E_1 = 1.43*\exp[-B_1*(Ca/S)]. \qquad (4.7.13)$$

Equation 4.7.12 is a proper expression for a specific fuel since coefficient B_2 may vary slightly for different fuels. Equation 4.7.13 then is more appropriate as a general form of the expression when more than one fuel is involved, or when the base line tests are not available and it is impossible, therefore, to determine the coefficient B_2 in Eq. 4.7.12 with an acceptable accuracy.

4.7.3 Discussion

Equations 4.7.10 and 4.7.13 have been used to fit the SO_2 emission data of Minto, Devco and Evans coals. These coals are among the most commonly used high sulphur coals and are also tested most extensively in the test programs. The results are given in Table 5.

For Minto coal, a separate model is also given for the tests conducted at Queen's University using coarse limestone, (1.72-1.98 mm). Excluding an abnormal datum at approximately 2500 ng/J, the data agree well with the following model as shown in Fig. 7:

$$E_1 = 1.43*\exp[-0.354*(Ca/S)]. \qquad (4.7.14)$$

The model for the rest of the data points plotted in this figure, i.e., the SO_2 emission observed in the pilot-plant tests with a limestone size of 0.21-1.11 mm, including both bubbling and circulating FBC, and the tests at the Summerside heating plant is found to be

$$E_1 = 1.43*\exp[-0.695*(Ca/S)]. \qquad (4.7.15)$$

Obviously, the coefficient B_1 in Eq. 4.7.13 is significantly affected by the size of the limestone used. The larger the size of the limestone particles, the higher the emission of SO_2 and therefore the smaller value of the coefficient B_1 is expected.

The coefficient B_1 is also affected by the recycle system as shown in Fig. 8. An appropriate model for Devco coal tests using the 0-6.3 mm limestone with recycle on is found to be

$$E_1 = 1.614*\exp[-0.872*(Ca/S)]. \quad (4.7.16)$$

For comparison, the model for the rest of the data plotted in Fig. 8 is

$$E_1 = 1.614*\exp[-0.515*(Ca/S)]. \quad (4.7.17)$$

These data are the results from tests using limestone with less fines as mentioned in Section 4.2. Apparently, a smaller value of the coefficient B_1 is expected when the recycle system is in operation.

The model for standardized SO_2 emission observed in pilot-scale bubbling FBC tests is:

$$E_1 = 1.43*\exp[-0.590*(Ca/S)]. \quad (4.7.18)$$

The pilot-plant tests consist of the tests with Minto, Devco and Evans coals with different sizes of limestone, including both the tests with and without the recycle system on. Significant scattering of the data are therefore expected. Since more than one fuel is involved, Eq. 4.7.13 is used. This model is compared to the pilot-scale test data in Fig. 10. A fairly good agreement between the model and the data can be seen.

The model for the tests conducted at the Summerside heating plant using Minto, Devco, Evans, Brogan and Novaco coals is found to be

$$E_1 = 1.43*\exp[-0.474*(Ca/S)]. \quad (4.7.19)$$

Again Eq. 4.7.13 is used because more than one fuel is involved and also no results of base line tests are available. This model is compared with the data in Fig. 9.

Also shown in this figure is the model representing the results from the pilot-scale tests, i.e. Eq. 4.7.18. Equation 4.7.19 agrees well with the data and with Eq. 4.7.18.

5. EXAMINATION OF NO_x EMISSION

5.1 INTRODUCTION

NO_x emission data were examined for and correlated to the same variables as those for SO_2, namely: fuel type, excess oxygen level, bed temperature, CO emission level, Ca/S molar ratio and facility. The effects are discussed in Sections 5.2 to 5.7. Unlike the situation where SO_2 emission is considered, the dependency of NO_x emission on facility is much more profound. In fact, the facility appears to have a major influence on each of the operating parameters examined. Therefore, the NO_x emission dependency on facility is correlated and discussed relative to each operating parameter. In addition, a general discussion and summary of facility dependency is given in Section 5.8.

Unlike SO_2 emission which is largely dependent upon the amount of sorbent added (Ca/S molar ratio), correlations between NO_x emission and the operating parameters are relatively weak. In order to reveal all the possible correlations correctly, special attention was given to the method of presentation of the emission. Both SO_2 and NO_x emissions may be measured by three commonly used parameters: the concentration (ppm) of the gas (NO_x or SO_2) in the flue gas, the mass (ng/J or lb/10^6 Btu) of the gas emitted and the fraction or percentage of the relevant element emitted or retained, e.g., fraction of fuel nitrogen converted to NO_x or

percentage of fuel sulphur captured.

Examination of the data indicates that the variation of the concentration of NO_x in the flue gas may not always reflect the amount of the NO_x emitted. The concentration of NO_x may be diluted if a large excess of oxygen is employed. A typical example is the NO_x emission from Evans coal shown in Figs. 27-30. In Figs. 27 and 29, the NO_x concentration in the flue gas shows different trends in the pilot-plant tests conducted at Queen's University and the tests conducted at the Summerside heating plant when either excess oxygen level or the equivalent quantity, the oxygen concentration in the flue gas, is used as the independent variable. However, the results of pilot scale and full scale tests agree quite well if the emission of NO_x is presented as the mass of NO_x emitted, Figs. 28 and 30. Obviously, the NO_x concentration in the flue gas observed at the Summerside heating plant is diluted due to the unusually high excess oxygen level employed. However, for most of the tests summarized in the present report, the excess oxygen level only varies over a narrow range and the dilution effect is insignificant. For these tests the concentration of NO_x in the flue gas may carry valuable information since it is directly measured in the experiment and subject to less errors than the other two methods of representing the amount of emission. Both the NO_x concentration in the flue gas and the mass of NO_x emitted are analyzed in the present work.

Instead of using a standardized emission as we did for SO_2 emission, a more commonly used parameter, the conversion of fuel nitrogen to NO_x, is adopted in this report in discussions where more than one fuel is involved. It will be shown in Section 5.2 that the effect of fuel nitrogen on this parameter is also largely eliminated.

A similar situation arises when considering the excess oxygen level, which also may be expressed as the concentration of oxygen in the flue gas as obtained directly by analysis. The excess oxygen level is calculated from the air flow rate and the stoichiometric amount of air as determined from the fuel feed rate. Under the assumption of complete combustion, neglecting the changes in the molar flow rate of the fluidizing gas caused by the calcination and sulphation reactions, Eq. 4.2.01 and Eq. 4.2.02, and the removal of the moisture in sampling of the flue gas, the relation between these two variables is

$$C_{02} = 21*Ex/(100 + Ex) \qquad (5.1.01)$$

where C_{02} is the molar concentration of oxygen in the flue gas, and Ex is the excess oxygen level, both presented as percent. As may be seen in Fig. 31, these two variables are not linearly correlated. The correlations of NO_x emission with these two variables may differ slightly as indicated in Figs. 28 and 30. The difference would be expected to be small for the pilot-plant tests due to the narrow range of the excess oxygen used. In the present work, however the

correlation of NO_x with each of these two variables is examined.

5.2 EFFECT OF FUEL NITROGEN

Nitrogen enters combustion systems as fuel nitrogen and atmospheric nitrogen. In the temperature range occurring in fluidized bed combustion, the oxidation of air nitrogen is negligible. The production of nitrogen oxides may thus be attributed entirely to reaction of fuel nitrogen [32]. The effect of fuel nitrogen on NO_x emission is therefore significant.

Summarized in Table 7 are the maximum, minimum and average values of the emission of NO_x observed in the forty test programs. The average emission of NO_x is found to increase with the fuel nitrogen and slightly depend on the fuel type and the facility used as shown in Fig. 32. The highest emission of NO_x is observed in the tests conducted at the Summerside heating plant. Under the assumption of zero NO_x emission for tests with fuels containing no nitrogen, our analysis gives a linear correlation between the emission of NO_x and the fuel nitrogen as

$$E_{20} = (0.296 \pm 0.019) * W_2 \qquad (5.2.01)$$

where E_{20} is the emission of NO_x in ng/J and W_2 is the fuel nitrogen, also in ng/J.

If, as is usually assumed, the NO_x emitted is completely composed of NO (molar mass 30) [32], the factor, Cv_N, for

conversion of fuel nitrogen to NO_x, may be related to the fuel nitrogen content (molar mass 14) and the mass of NO_x emitted by

$$Cv_N = (14/30)*(E_{20}/W_2). \qquad (5.2.02)$$

Then the coefficient of 0.296 in Eq. 5.2.01 suggests an average value of 0.138 for conversion of fuel nitrogen to NO_x.

Quantity Cv_N does not vary significantly with fuel nitrogen since NO_x emission is proportional to fuel nitrogen as indicated in correlation Eq. 5.2.01. This quantity is used in later discussions where more than one fuel is compared.

5.3 EFFECT OF EXCESS OXYGEN

Examination indicates that NO_x emission increases with excess oxygen in many of the tests. However, the trend is not consistent and appears to depend on the fuel type and the facility used.

An increase in NO_x emission with excess oxygen is observed consistently in the tests with Evans coal, Figs. 28 and 30, Devco coal, Fig. 33, Mt Klappan coal, Fig. 34 and heavy oils, Fig. 35. For some fuels, this trend is shown only in some of the tests conducted, e.g. the bubbling FBC tests with Syncrude coke, Fig. 36, and bubbling FBC tests with Highvale and Minto coals conducted at Queen's University, Figs. 37, 38 and 39. This increase with excess oxygen is also observed in the tests with Poplar River lignite, Fig. 40,

Saskatchewan petroleum coke and the coal/water slurry, Figs. 38 and 39. However, this trend is not observed in the tests with Onakawana lignite, Byron Creek coal and Suncor coke, see Appendices C and D Figs. C106, D106, C606, D606, C111, D111, C112 and D112.

This inconsistent variation of NO_x emission with excess oxygen is considered to be largely the result of the facility used, although errors in measurements may also be partly responsible. As indicated in Figs. 33 to 37, an increase in NO_x emission of each fuel with excess O_2 is clearly shown only in tests conducted in one or two combustors. For example, for Devco coal, the trend is most clearly shown in the tests conducted at the Queen's University bubbling FBC pilot plant, Fig. 33; for Mt Klappan coal, the tests conducted at the Queen's University bubbling FBC pilot plant and at the UBC circulating FBC pilot plant, Fig. 34; for heavy oils, the tests conducted at UBC circulating FBC pilot plant, Fig. 35; and for Syncrude coke, the tests conducted at the Queen's University and the Mark II bubbling FBC pilot plants, Fig. 36. It is clear that both the variation with excess oxygen and the magnitude of the NO_x emission may differ from combustor to combustor for a given fuel. The most typical example is the result with Syncrude coke, Fig. 36. The NO_x emission from the circulating FBC pilot plant in Finland is considerably less (20-220 ng/J over the excess oxygen level of 10 to 60%) than that observed at the bubbling FBC pilot

plants at CCRL (Mark II) and at Queen's University (60-340 ng/J over the excess oxygen level of -30 to 10%). Furthermore, the emission from the Finland circulating FBC pilot plant does not increase with excess oxygen level as is the case for the bubbling FBC tests with the fuel.

The facility dependency of the effect of excess oxygen on NO_x emission is more evident when the emission data are grouped according to the facility used. An increase in NO_x emission with excess oxygen level is consistently observed in the tests conducted at Queen's University, Figs. 38 and 39. This includes the tests with five different coals, two petroleum cokes and one non-conventional fuel, the coal/water slurry. The concentration of NO_x in the flue gas is exceptionally high when Syncrude coke is tested due to the high nitrogen content of the fuel, Fig. 38. When conversion of fuel N to NO_x is used as the dependent variable, all tests appear to give similar results, Fig. 39.

The UBC circulating FBC pilot plant produces similar results, Fig. 40. The increase of NO_x emission with excess oxygen level is consistently observed in the tests with four different coals and two pitches conducted at this plant.

However, the NO_x emission observed in both the Mark I and Mark II combustors shows basically no identifiable trend with excess oxygen level, with the possible exception of those tests with Line Creek coal conducted at the Mark I pilot plant, see Appendices C and D Figs. C111, C611, D112

and D612.

The NO_x emission observed at the Summerside heating plant presented as ppm decreases consistently with oxygen level in the flue gas due to the dilution effect, Fig. 41. The trend is still slightly downwards even after transforming the dependent variable into conversion of fuel nitrogen to NO_x, Fig. 42. This is just the reverse to the observation made at Queen's University and UBC.

5.4 EFFECT OF BED TEMPERATURE

An increase of NO_x emission with bed temperature has been observed in tests with Minto coal, Devco coal, Onakawana lignite and some of the tests with Highvale coal and Syncrude coke, Figs. 43-47. However, no such trend could be identified in the tests with Mt Klappan coal and the heavy oils, see Appendices C and D Figs. C205, C208, D205 and D208.

The trends observed in the tests with Minto coal conducted at Queen's University and CCRL are represented by the two lines calculated by linear regression analysis, Fig. 43. No trend has been observed in the tests conducted at UBC and the Summerside heating plant with the fuel because of the narrow range of the bed temperature employed. The NO_x emission observed in the tests with Devco coal also shows an increase with bed temperature, although most of the tests are performed over a relatively narrow temperature range (840-870 Deg. C), Fig. 44. The NO_x emission observed in the tests with

Onakawana lignite conducted in the bubbling FBC combustors Mark I and Mark II increases slightly with bed temperature as shown in Fig. 45 with the exception of one point at about 200 ng/J. The increase is also observed in some of the tests with Highvale coal and Syncrude coke, Figs. 46 and 47. However, this trend is not shown in the tests with either Highvale coal or Syncrude coke conducted at the Queen's University bubbling FBC plant. A facility dependence is also suggested by the difference in the magnitude of NO_x emission observed at different plants when a given fuel is tested. This is shown in tests with almost every fuel presented in Figs. 43-47.

Figures 48-51 show different correlations between NO_x emission and bed temperature observed in four combustors, which further confirms this facility dependence of bed temperature effect on the NO_x emission. Figure 48 shows the conversion of fuel nitrogen to NO_x as a function of bed temperature observed in the tests with five different fuels conducted at the Mark I bubbling FBC pilot plant. A rather close correlation is evident. Figure 49 shows the results of the tests with six different fuels conducted at the UBC circulating FBC pilot plant. A fairly strong correlation is evident with the conversion of fuel nitrogen to NO_x falling to low levels at low bed temperature. The results from the Mark II bubbling FBC pilot plant are less conclusive. The conversion of fuel nitrogen to NO_x is strongly correlated to

the bed temperature, showing a slight increasing trend, in the tests with Byron coal and Onakawana lignite as indicated in Fig. 50. But, the correlation is poor in the tests with the heavy oils and not conclusive in the tests with Devco coal due to the narrow range of the temperature employed. No correlation between conversion of fuel nitrogen to NO_x and the bed temperature is observed in the tests on six different coals conducted at the Summerside heating plant, Fig. 51. Nor is a correlation evident in the tests with eight different fuels conducted at Queen's University except the tests with Minto coal and the Saskatchewan petroleum coke, see Appendices C and D Figs. C210 and D210.

5.5 EFFECT OF FUEL FIRING RATE

The NO_x emission shows no correlation with the fuel firing rate, see Appendices C and D, except for the tests with Evans coal conducted at Queen's University, Fig. 52, and the NO_x concentration in the flue gas observed in the tests conducted at the Summerside heating plant, Fig. 53. The decrease of NO_x emission with the fuel firing rate in the tests with Evans coal conducted at Queen's University is more likely the result of the excess oxygen level which decreases with the increasing fuel firing rate as shown in Fig. 54. The increasing NO_x concentration in the flue gas observed in the Summerside heating plant is likely the result of the dilution effect. The correlation disappears after transforming the

dependent variable into conversion of fuel nitrogen to NO_x, Fig. 55. Thus, there is virtually no correlation between these two variables in any of the test programs.

5.6 RELATIONSHIP TO CO EMISSION LEVEL

The NO_x emission shows a consistent decrease with increase in CO emission. A few exceptions are observed in tests where the CO emission is relatively low and only covers a narrow range, making these observations unreliable and the results inconclusive. The CO emission level is not available in six test programs, i.e., those tests conducted at Queen's University with Devco, Evans, Kentucky #9, and Mt Klappan coals, and the tests conducted at UBC with H-oil pitch.

Figures 56-60 show the relationships of the NO_x emission to the CO emission level observed in the tests with Minto coal, Devco coal, Onakawana lignite, Syncrude coke and the heavy oils at various facilities.

A close correlation between these two variables is evident in the tests with Minto coal conducted at Queen's University and the Summerside heating plant as indicated in Fig. 56. The magnitude of the NO_x emission observed in the tests with this fuel conducted at the Mark I bubbling FBC pilot plant and the UBC circulating FBC pilot plant are slightly lower than that observed at Queen's University and the Summerside heating plant. Dependency of NO_x emission on facility is likely to be responsible for the difference in

the magnitude of the NO_x emission. Since only very low CO emission is observed in the tests with this fuel conducted at the Mark I bubbling FBC pilot plant and the UBC circulating FBC pilot plant, lower than 700 ppm except one point at 1600 ppm, no consistent trend for the NO_x emission is obvious in these tests.

A strong correlation is found between NO_x and CO emission levels in the tests with Onakawana lignite at the Mark I and Mark II bubbling FBC pilot plants, Fig. 57, while the tests with Devco coal show a reasonably strong correlation, Fig. 58.

The emission of NO_x observed in the tests with Syncrude coke conducted at the bubbling FBC pilot plants, Mark II and that at Queen's University, and the circulating FBC pilot plant in Finland show a similar trend in that the NO_x emission falls to low levels at high levels of CO emission, Fig. 59. Again the difference in the magnitude of the NO_x emission should be explained by the facility dependency rather than by the relationship to the CO emission level. Similar phenomena can be found in the tests with the heavy oils, with the exception of bitumen, conducted at the Mark II bubbling FBC pilot plant, see Figs. C408 and D408 in Appendices C and D.

Although the magnitude of the NO_x emission may vary slightly depending on the facility used, the decrease of NO_x emission with increasing CO emission level is observed in

almost every combustor. Typical examples are shown in Figs. 60-62.

The results observed at the Summerside heating plant are shown in Figs. 60 and 61. Strong correlations are evident between the emission levels of NO_x and CO regardless as to whether the NO_x emission is presented as concentration in the flue gas or conversion of fuel nitrogen to NO_x. A fairly strong correlation is found in the tests with three different coals, two petroleum cokes and a coal/water slurry conducted at the Queen's University bubbling FBC plant as shown in Fig. 62. Similar correlations exist for the tests with Devco coal, Byron Creek coal, Onakawana lignite and heavy oils conducted at the Mark II bubbling FBC pilot plant, and the tests with Minto coal, Line Creek coal, Highvale coal, Onakawana lignite and Suncor coke conducted at the Mark I bubbling FBC pilot plant, see Figs. C411, D411, C412 and D412 in Appendices C and D. This also explains the results obtained in the tests conducted in the circulating FBC combustor at UBC. The conversion of the fuel nitrogen to NO_x observed in the tests conducted at the UBC circulating FBC pilot plant is inconclusive due to the narrow range of CO emission, less than 1000 ppm, see Appendices C and D Figs. C413 and D413.

A high CO emission level is usually related to incomplete combustion or high content of fine char in the gas. It seems, therefore, that the NO_x emission is reduced significantly by either high CO content or high char content

existing in the flue gas due to the thermodynamically favoured reactions [33]:

$$NO_{(g)} + C_{(s)} \rightarrow CO_{(g)} + (1/2)N_{2(g)} \qquad (5.6.01)$$

$$2NO_{(g)} + C_{(s)} \rightarrow CO_{2(g)} + N_{2(g)} \qquad (5.6.02)$$

and possibly homogeneous reactions catalyzed by char and CaO [34-37], mainly:

$$NO_{(g)} + CO_{(g)} \rightarrow CO_{2(g)} + (1/2)N_{2(g)}. \qquad (5.6.03)$$

At low levels of CO emission, i.e., lower than approximately 600 ppm for plant Mark I, 1800 ppm for Mark II and the plant at Queen's University, the NO_x emission is more likely to be determined by mechanisms other than the reduction by CO gas or char fines, and the NO_x emission data are therefore more scattered at low CO emission. This also explains the trendless NO_x emission data observed at the UBC circulating FBC pilot plant.

5.7 EFFECT OF Ca/S MOLAR RATIO

The effect of Ca/S molar ratio is examined through the results of the tests with extensive addition of limestone given in Table 5. Although evidence of the catalytic reduction of NO_x by either H_2 or CO gas over calcined limestone in combustors has been reported [34-37], our analysis shows no consistent trend for NO_x emission with Ca/S molar ratio.

The effect of limestone on NO_x emission seems to depend on the fuel type. An increase of NO_x emission with Ca/S molar

ratio is observed in the tests with Minto coal, Fig. 63. The results obtained from different pilot plants agree well, including both bubbling and circulating FBC results. The emission from the Summerside heating plant increases with Ca/S molar ratio very sharply. Because the Ca/S molar ratio employed in the tests with this fuel conducted at this plant only covers a narrow range such a sharp upwards trend needs further confirmation. No trend is found in the tests with Devco coal, Fig. 64. The results for Evans coal are inconsistent. The NO_x emission increases with increasing Ca/S ratio in the tests with Evans coal conducted at the Summerside heating plant, while the emission observed at Queen's University varies in the opposite direction as shown in Fig. 65. The results in pilot plant tests with Syncrude coke show an increase with Ca/S molar ratio, Fig. 66. But no trend has been observed in the tests conducted at the circulating FBC pilot plant in Finland. The NO_x emission in the tests with heavy oils shows a slight increase with the Ca/S molar ratio except for the tests with the #6 oil and the tests with CANMET pitch conducted at the Mark II pilot plant as indicated in Fig 67. The emission of NO_x is lower when limestone is added in the tests with CANMET pitch conducted at the bubbling Mark II FBC pilot plant while no correlation seems to exist between these two variables in the tests with #6 oil.

The variation of NO_x emission with Ca/S molar ratio is

also dependant on the facility used. Figure 68 shows a consistent increase of NO_x emission with the Ca/S molar ratio observed at the circulating FBC pilot plant at UBC. The fuels tested at this pilot plant include four different kinds of coals and two types of pitches. However, no consistent trend exists in the tests conducted at the Summerside heating plant, Fig 69. Although an increasing conversion of fuel nitrogen to NO_x with Ca/S molar ratio is evident in the tests with Evans coal conducted at this plant, Fig. 65, the conversion of fuel nitrogen to NO_x shows no trend with Ca/S molar ratio for a Ca/S molar ratio less than approximately 4.5. No consistent trend is found for the tests conducted at the Mark II pilot plant and the Queen's University pilot plant, see Figs. C511, D511, C510 and D510 in Appendices C and D. The NO_x emission observed at the Mark II pilot plant shows a very slight variation or no variation with Ca/S molar ratio, while the emission observed at Queen's University is much more scattered with no noticeable pattern. Only one test program with extensive limestone addition was performed at the Mark I pilot plant, namely those tests with Minto coal. An increase of NO_x emission with Ca/S molar ratio is evident in these tests as shown in Fig 63.

5.8 DEPENDENCE OF NO_x EMISSION ON FACILITY

As mentioned in previous sections, the magnitude of NO_x emission varies with facility. More important, the facility

used also determines the effect of a given operating parameter on NO_x emission.

Table 8 summarizes the effect of five operating parameters on NO_x emission observed in each of the six combustors. The common trends observed among these facilities are: 1) a decrease in NO_x emission with an increase in CO emission level; 2) no effect of fuel firing rate on NO_x emission; 3) an increase or non variance of NO_x emission with bed temperature; 4)little or no effect of the Ca/S molar ratio; and 5) a slight decrease in or no effect on the NO_x emission by excess oxygen level.

A close examination indicates that the slight decrease in NO_x emission with excess oxygen level observed at the Summerside heating plant does not contradict the observation made at Queen's University. It seems that the increase of NO_x emission with excess oxygen level may level off at high excess oxygen level as indicated in the tests with Evans coal shown in Figs. 28 and 30. Therefore, the NO_x emission observed at the Summerside heating plant may not have to increase with oxygen level in the flue gas due to the unusually high excess oxygen level employed, 83% to 270% at the Summerside heating plant compared to -22% to 67% at Queen's University.

Moreover, a high excess oxygen level enhances elutriation of char fines leading to a slight increase of CO emission which may reduce the NO_x emission. Fig. 70 shows the

effect of oxygen level in the flue gas on the CO emission level observed at the Summerside heating plant and the Queen's University bubbling FBC pilot plant. Generally, the oxygen level in the flue gas observed at the Summerside heating plant is higher than 8% while the oxygen level observed at Queen's University is lower than 8%. The CO emission observed at Queen's University is likely to be caused largely by incomplete combustion. It is thus reduced at high oxygen levels, although low CO emission levels are also observed at low oxygen levels. Therefore, the increase of NO_x emission with excess oxygen level observed at this pilot plant as indicated in Figs. 38 and 39 is consistent with the decrease of the emission with CO emission indicated in Fig. 62. The slight decrease of conversion of fuel nitrogen to NO_x with oxygen level in the flue gas observed at the Summerside heating plant as indicated in Fig. 42 is also consistent with its decrease with CO emission level as shown in Fig. 60, since the CO emission observed at this plant, while remaining low in magnitude, increases slightly with the oxygen level in the flue gas.

Although generation of NO_x may depend on facility, a possible explanation for such facility dependence in FBC combustor performance is incomplete NO_x removal primarily through the reactions described by Eq. 5.6.01, Eq. 5.6.02 and Eq. 5.6.03. For bubbling FBC, the emission of NO_x at the combustor exit or stack will depend on the height of the

freeboard, the temperature in freeboard and the amount of elutriated char fines if the freeboard is not high enough to allow completion of these reactions to equilibrium. For circulating FBC, the height of the combustion chamber is likely to determine if the equilibrium is reached. NO_x emission is likely to depend on facility if the equilibrium is not attained.

6. CONCLUSION AND REMARKS

6.1 SO_2 EMISSION

Emission of SO_2 observed in the six fluidized bed combustors, including both bubbling and circulating types, and of pilot and commercial size, is found to be largely determined by sulphur content of the fuel and the amount of limestone added.

In combustion without addition of limestone, the SO_2 emission is found to be proportional to the sulphur content of the fuel. Approximately 28.5% of the fuel sulphur is lost in solid products of the combustion leaving approximately 71.5% of the fuel sulphur to be emitted as pollutants, mainly as SO_2. Thus, in order to meet the federal guideline for SO_2 emission (258 ng/J), limestone addition is necessary only for fuels with sulphur content higher than 184 ng/J.

In combustion of high sulphur fuels with addition of limestone, the SO_2 emission is largely determined by the Ca/S molar ratio. The emission decreases exponentially with Ca/S molar ratio. This may be represented most accurately by the equation

$$E_{10} = 2*B_2*W_1*\exp[-B_1*(Ca/S)] \qquad (4.7.10)$$

where E_{10} is the emission of SO_2 in ng/J, W_1 is the sulphur content of the fuel in ng/J, B_1 and B_2 are coefficients of the model. A value of 0.715 is suggested for the coefficient B_2. A recycle system and limestone of smaller size enhance the

effect of Ca/S molar ratio. A relatively smaller value of the coefficient B_1 should be assigned under these conditions.

Circulating FBC systems are found to be more effective in sulphur capture due mainly to the smaller size of limestone used. However, significant improvement is observed only in combustion of fine solid fuels (e.g., Syncrude coke) and liquid fuels. Among the bubbling FBC systems examined, the dependency of sulphur capture on facility is relatively weak.

The effect of bed temperature is significant only when a wide range of bed temperature (e.g., above 1050 deg. C) is employed. The effect is relatively flat in the most commonly used temperature range of 800-900 deg. C.

The effect of fuel firing rate, excess oxygen level, CO and NO_x emission levels are usually negligible, unless they cause a significant change in other more influential operating parameters, e.g., a unusually high fuel firing rate may cause a significant increase of bed temperature leading to increasing SO_2 emission.

6.2 NO_x EMISSION

Unlike SO_2 emission, correlations between NO_x emission and the operating parameters are relatively weak. A fairly strong linear correlation exists between NO_x emission and fuel nitrogen. The correlation with fuel nitrogen indicates that the average conversion of fuel nitrogen to NO_x is 0.138.

Therefore, NO_x emission may be controlled by choosing fuels with low nitrogen content.

The most consistent regularity is the correlation between NO_x emission and CO emission level. The NO_x emission level always falls to low levels at high levels of CO emission. NO_x emission data are very scattered at low CO emission level. The trend is less clear in tests where CO emission is low and only covers a narrow range. Apparently, the emission can be minimized by keeping the exhaust CO level high.

An increase in NO_x emission with excess oxygen is also observed. However, this trend is clearly shown only in the tests conducted at the Queen's University bubbling FBC pilot plant and the UBC circulating FBC pilot plant. There is evidence to indicate that the effect of the excess oxygen on NO_x emission levels off at high excess oxygen levels. At high excess oxygen, the CO emission may increase with increasing excess oxygen due probably to enhanced elutriation of char fines. NO_x emission may therefore decrease with increasing excess oxygen level at high excess oxygen levels. This phenomenon is observed at the Summerside heating plant. However, the effect of oxygen level on NO_x emission may not always be related to CO emission. As shown in the tests conducted at the UBC circulating FBC pilot plant, the NO_x emission increases with excess oxygen level while showing no trend with CO emission level. As a result of these

observations, it is recommended that the FBC unit be operated at the lowest excess oxygen level which still gives acceptable combustion in order to reduce NO_x emission.

Increasing NO_x emission with bed temperature is also observed in both bubbling and circulating FBC tests except those tests conducted at the Summerside heating plant and the Queen's University bubbling FBC pilot plant where no apparent correlation of NO_x emission with bed temperature is observed. However, operating at a low temperature is considered to be a practical strategy for reducing NO_x emission.

NO_x emission shows no consistent variation with the Ca/S molar ratio. An increase of NO_x emission with Ca/S molar ratio is observed in some of the tests, primarily those conducted at the UBC circulating FBC pilot plant. Such behaviour contradicts the catalysis effect of CaO on reduction of NO_x by reducing gases in the combustor reported in the literature. The reason for such behaviour is not clear.

Unlike SO_2 emission which can be easily removed by sorbent addition, NO_x emission is determined by formation and destruction processes occurring in the combustor. Unfortunately, the mechanism of these processes does not seem to be fully understood. Evidently, the effects of CO emission, excess oxygen and bed temperature vary strongly with facilities which makes prediction of NO_x emission very difficult. Further research on formation and destruction of

NO_x in combustors is therefore suggested. This should include a study of structural effects and the interaction of various structural designs with various operating parameters such as excess oxygen, bed temperature etc.

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TABLE 1 SUMMARY OF THE TEST PROGRAMS

SERIAL NO.	FUEL	FACILITY USED	NO. OF RUNS	SOURCE REPORT
1	MINTO BITUMINOUS	BUBBLING FBC AT QUEEN'S UNIV.	19	QFBC. TR. 83.1 [1]
2	MINTO BITUMINOUS	BUBBLING FBC AT CCRL (MARK I)	18	ERP/ERL 81-36(J) [10]
3	MINTO BITUMINOUS	SUMMERSIDE HEATING PLANT	3	SUMMERSIDE TEST RESULTS [17]
4	MINTO BITUMINOUS	CIRCULATING FBC AT UBC	9	CONTRACT 24ST. 23440-6-9007 [19]
5	MINTO BITUMINOUS	CIRCULATING FBC AT BUC	7	CONTRACT 52SS. 23440-7-9136 [21]
6	DEVCO BITUMINOUS	BUBBLING FBC AT QUEEN'S UNIV.	4	QFBC. TR. 83.1 [1]
7	DEVCO BITUMINOUS	BUBBLING FBC AT QUEEN'S UNIV.	8	QFBC. TR. 85.1 [2]
8	DEVCO BITUMINOUS	BUBBLING FBC AT CCRL (MARK II)	36	ERP/ERL 85-44 (OPJ) [12]
9	DEVCO BITUMINOUS	SUMMERSIDE HEATING PLANT	3	SUMMERSIDE TEST RESULTS [17]
10	EVANS BITUMINOUS	BUBBLING FBC AT QUEEN'S UNIV.	16	QFBC. TR. 85.1 [2]
11	EVANS BITUMINOUS	SUMMERSIDE HEATING PLANT	3	SUMMERSIDE TEST RESULTS [17]
12	EVANS BITUMINOUS	SUMMERSIDE HEATING PLANT	3	U.S. EPA TEST RESULTS [18]
13	BROGAN BITUMINOUS	SUMMERSIDE HEATING PLANT	3	SUMMERSIDE TEST RESULTS [17]
14	NOVACO BITUMINOUS	SUMMERSIDE HEATING PLANT	3	SUMMERSIDE TEST RESULTS [17]
15	KENTUCKY NO. 9 BITUMINOUS	BUBBLING FBC AT QUEEN'S UNIV.	4	QFBC. TR. 85.1 [2]

TABLE 1 SUMMARY OF THE TEST PROGRAMS (CON'T)

SERIAL NO.	FUEL	FACILITY USED	NO. OF RUNS	SOURCE REPORT
16	BYRON CREEK BITUMINOUS	BUBBLING FBC AT CCRL (MARK II)	17	ERP/ERL 83-12 (TR) [11]
17	LINE CREEK BITUMINOUS	BUBBLING FBC AT CCRL (MARK I)	24	ERP/ERL 81-32 (TR) [9]
18	HIGHVALE COAL SUB-BITUMINOUS	BUBBLING FBC AT QUEEN'S UNIV.	7	QFBC. TR. 87.3 [3]
19	HIGHVALE COAL SUB-BITUMINOUS	BUBBLING FBC AT CCRL (MARK I)	18	ERP/ERL 81-36(J) [10]
20	HIGHVALE COAL SUB-BITUMINOUS	CIRCULATING FBC AT UBC	8	CONTRACT 52SS. 23440-7-9136 [21]
21	WASHED MT KLAPPAN ANTHRACITE	BUBBLING FBC AT QUEEN'S UNIV.	3	QFBC. TR. 87.4 [4]
22	MT KLAPPAN ANTHRACITE	BUBBLING FBC AT QUEEN'S UNIV.	3	QFBC. TR. 87.4 [4]
23	MT KLAPPAN ANTHRACITE	CIRCULATING FBC AT UBC	6	CONTRACT 52SS. 23440-7-9136 [21]
24	ONAKAWANA LIGNITE	BUBBLING FBC AT CCRL (MARK I)	8	ERP/ERL 81-30 (CF) [8]
25	ONAKAWANA LIGNITE	BUBBLING FBC AT CCRL (MARK II)	9	ERP/ERL 87-67 (OPJ) [15]
26	POPLAR RIVER LIGNITE	CIRCULATING FBC AT UBC	4	CONTRACT 52SS. 23440-7-9136 [21]
27	WASHERY REJECT FROM DEVCO COAL	BUBBLING FBC AT CCRL (MARK II)	12	ERP/ERL 87-71 (TR) [16]
28	SYNCRUDE COKE	BUBBLING FBC AT QUEEN'S UNIV.	9	QFBC. TR. 85.1 [2]
29	SYNCRUDE COKE	BUBBLING FBC AT CCRL (MARK II)	7	ERP/ERL 86-74 (TR) [13]
30	SYNCRUDE COKE	CIRCULATING FBC PILOT PLANT IN KARHULA FINLAND	18	CONTRACT 23SQ. 23440-4-9239 [20]

TABLE 1 SUMMARY OF THE TEST PROGRAMS (CON'T)

SERIAL NO.	FUEL	FACILITY USED	NO. OF RUNS	SOURCE REPORT
31	SUNCOR COKE	BUBBLING FBC AT CCRL (MARK I)	10	ERP/ERL 81-27 (TR) [7]
32	SASKATCHEWAN PETROLEUM COKE	BUBBLING FBC AT QUEEN'S UNIV.	14	QFBC. TR. 87.5 [5]
33	COAL/WATER SLURRY	BUBBLING FBC AT QUEEN'S UNIV.	17	QFBC TR. 87.6 [6]
34	NO. 6 OIL	BUBBLING FBC AT CCRL (MARK II)	22	ERP/ERL 87-22 (CF) [14]
35	CANMET PITCH	BUBBLING FBC AT CCRL (MARK II)	13	ERP/ERL 87-22 (CF) [14]
36	CANMET PITCH	CIRCULATING FBC AT UBC	4	CONTRACT 24ST. 23440-6-9007 [19]
37	CANMET PITCH	CIRCULATING FBC AT UBC	6	CONTRACT 52SS. 23440-7-9136 [21]
38	H-OIL PITCH	CIRCULATING FBC AT UBC	3	CONTRACT 24ST. 23440-6-9007 [19]
39	H-OIL PITCH	CIRCULATING FBC AT UBC	6	CONTRACT 52SS. 23440-7-9136 [21]
40	BITUMEN	BUBBLING FBC AT CCRL (MARK II)	3	ERP/ERL 87-22 (CF) [14]

TABLE 2 ANALYSIS OF THE FUELS TESTED

FUEL TYPE	FUEL NAME	VM %	FC %	MOIS %	C %	H %	N %	S %	O %	ASH %	HHV MJ/KG
HIGH VOLATILE A BITUMINOUS	MINTO	32.1	47.7	1.0	65.7	4.3	0.8	8.1	3.5	19.7	27.1
	DEVCO	33.0	49.5	3.7	65.2	4.2	1.2	4.8	5.7	17.0	26.2
	BROGAN	35.5	54.4	1.4	64.9	4.1	1.2	8.7	6.4	16.6	27.0
	NOVACO	33.4	46.9	1.3	61.0	4.3	1.2	4.7	8.3	19.6	23.3
	KENTUCKY NO. 9	35.0	46.9	7.1	64.8	4.6	1.3	4.3	7.9	18.0	25.9
HIGH VOLATILE B BITUMINOUS	EVANS	34.8	51.7	1.5	68.5	4.4	1.2	6.5	7.4	11.2	27.6
MEDIUM VOLATILE BITUMINOUS	BYRON CREEK	27.0	56.0		71.0	4.1	1.1	0.6	6.3	17.0	27.0
LOW VOLATILE BITUMINOUS	LINE CREEK	19.8	61.5		69.8	3.8	0.9	0.3	6.5	18.7	27.5
SUB-BITUMINOUS	HIGHVALE	33.5	50.0	17.0	62.4	3.2	0.7	0.3	17.1	16.4	23.1
ANTHRACITE	MT KLAPPAN (WASHED)	7.0	84.3	10.0	86.2	2.5	1.1	0.7	0.8	8.7	30.5
	MT KLAPPAN (UNWASHED)	6.5	66.2	12.6	65.7	2.1	0.9	0.6	3.4	27.4	24.3
LIGNITE	ONAKAWANA	38.6	36.9	39.0	52.6	3.8	0.8	1.3	17.1	24.5	20.2
	POPLAR RIVER	35.1	37.0	15.5	59.0	3.6	0.7	0.9	21.1	14.7	24.0
WASHERY REJECT	DEVCO	31.9	45.3	7.9	60.8	4.2	1.3	5.2	5.8	22.8	24.1
PETROLEUM BY-PRODUCT COKE	SYNCRUDE	6.3	86.0	2.1	81.9	1.4	1.8	6.8	0.7	7.7	29.5
	SUNCOR	13.0	82.6	4.4	83.2	3.5	1.4	5.7	1.8	4.4	33.5
	SASKA-TCHEWAN	10.0	89.0	8.4	92.9	4.9	1.2	2.9	0.0	1.1	34.8
COAL/WATER SLURRY	CAPE BRETON	35.1	57.0	55.4	79.6	4.9	1.3	3.1	3.2	7.9	30.8
HEAVY OIL	NO. 6 OIL				86.1	10.8	0.3	2.5	0.2	0.2	42.9
	CANMET PITCH				87.4	9.3	0.7	2.3	0.5	2.0	41.4
	HIGH OIL PITCH				86.4	7.9	1.0	2.3	2.3	0.1	41.0
	BITUMEN				82.0	9.9	0.5	6.4	0.1	1.8	40.6

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS

TEST NO.	BED TEMP. C MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
1. MINTO COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 83.1 [1]:												
821116	850		1.25	-6.5	5363	2500		240		2700		1.8
830106	845		2.06	3.8	5106	2500		240		1100		4.0
830112	820		1.60	-0.1	5674	2400		200		3700		0.5
830124	820		2.10	-2.8	6003	1750		260		2800		2.1
830126	805		4.25	1.9	5527	0		390		1600		2.1
830127	835		2.66	3.3	5546	463		370		1600		1.3
830201	825		2.24	-1.5	6095	700		255		2000		1.0
830202	840		3.60	2.0	6058	174		275		1850		0.6
830215	860		2.24	14.7	7504	1250		310		1700		3.6
830216	865		2.92	14.9	7486	850		323		1170		3.6
830217	840		2.95	20.5	7284	750		370		800		4.8
830218	860		2.70	24.0	6955	2750		350		500		5.9
830224	855		3.56	21.8	6955	1270		350		1050		5.0
830225	940		3.10	19.3	7138	1350		340		1000		5.1
830226	920		4.47	17.2	7211	750		260		350		2.7
830322	840		2.14	1.2	5692	1350		325		1100		3.8
830324	855		1.87	0.8	6296	1850		260		2600		1.7
830329	855		3.73	-1.4	6992	180		390		1320		1.4
830330	850		3.57	-9.2	6845	260		273		200		0.6
2. MINTO COAL TESTS AT CCRL (MARK I), ERP/ERL 81-36(J) [10]:												
7	849		0	0.9	5823	5976		230		650		4.9
8	853		0	35.5	5853	6610		200		1600		2.5
9	763		0	45.0	5829	5928		90		300		5.1
10	752		0	32.9	5504	6642		55		400		2.4
11	955		0	49.5	8881	5704		200		200		5.1
12	956		0	31.4	9308	6489		200		150		2.5
13	856		0	38.6	9146	5781		60		150		5.0
14	851		0	27.4	9170	6399		25		100		2.4
15	745		0	32.5	9614	6505		10		350		4.9
16	760		0	26.5	9332	6797		13		400		2.3
17	764		0	64.0	3107	6506		60		350		5.0
18	758		0	56.3	2884	6693		22		150		2.5
A1	846		1.72	49.1	6243	1750		23		200		5.1
A2	845		1.72	42.0	5775	2175		130		175		2.5
A3	854		3.02	52.9	6039	661		180		175		4.9
A4	842		3.02	48.4	5486	788		140		210		2.5
A5	845		4.32	63.0	5324	75		230		260		5.3
A6	852		4.32	48.4	5679	150		193		175		2.3

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. C MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
3. MINTO COAL TESTS AT SUUMMERSIDE HEATING PLANT [17]:												
100% MCR	850	35.7	2.39	86.9	6031	739	125	393	95	390	202	9.8
65% MCR	867	8.3	1.98	104.1	7716	712	118	271	43	498	123	10.0
23% MCR	840	15.3	1.62	201.8	2965	787	195	115	42	1280	557	14.3
4. MINTO COAL TESTS IN C IRCULATING FBC AT UBC, CONTRACT 24ST 23440-6-9007 [19]:												
1	866		1.36	5.4	22682	1836		130		245		2.0
2	869		1.36	15.0	23988			138		245		3.0
3	878		1.36	-1.1	26957			136		245		3.2
4	891		1.36	6.9	23869			145		245		3.5
5	868		1.36	10.6	30282			146		245		3.7
6	895		1.36	18.2	30638			140		245		3.4
7	872		1.63	12.2	21850	1576		113		15		3.4
8	846		2.17	7.8	22325	1205		134		10		3.4
9	875		2.72	5.1	25532	770		149		10		3.5
5. MINTO COAL TESTS IN CIRCULATING FBC AT UBC, CONTRACT 52SS 23440-7-9136 [21]:												
RUN3-C1	875		3	14.7	24600	589.3		123		58		2.6
RUN16-1	884		3	19.4	23070	53.7		261		99		3.5
RUN16-2	894		3	16.8	23540	52.7		225		69		3.1
RUN16-3	895		1.8	18.1	23305	775.5		193		98		3.3
RUN16-4	887		1.8	24.3	22128	1099		263		129		4.2
RUN16-5	870		1.8	20.8	20598	557.5		203		120		3.7
RUN16-6	893		3	16.8	21304	529.1		183		60		3.1
6. DEVCO COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 83.1 [1]:												
830309	860		3.00	21.1	4618	750		410		1300		3.0
830310	870		2.28	29.6	4301	1200		320		470		6.0
830315	865		3.52	34.4	5983	450		410		300		7.4
830316	850		2.27	43.6	5586	1050		362		350		9.2
7. DEVCO COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 85.1 [2]:												
841127	851		3.43	19.1	6835	751	49	429	4			5.0
841204	851		3.14	9.2	7391	448	37	383	7			4.3
841218	853		2.98	9.4	7440	958	45	346	6			4.6
841219	857		3.20	14.4	7162	884	49	335	5			4.2
850107	854		3.39	14.1	4301	601	26	320	6			2.8
850115	864		1.91	27.4	3818	1132	61	376	6			3.9
850129	868		2.14	32.8	5914	556	25	603	5			6.4
850304	866		2.86	23.2	3988			275				

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. C MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
8. DEVCO COAL TESTS AT CCRL (MARK II), ERP/ERL 85-44 (OPJ) [12]:												
BDC1	860		0	-2.4	9850	4408		475		1600		4.3
BDC2	860		0	-0.2	9632	4450		468		1300		4.2
BDC3	855		0	-7.4	7266	4569		416		1580		3.5
BDC4	858		0	-1.0	6796	3816		439		1631		3.5
BDC5	853		0	-12.5	4397	5081		506		777		3.3
DC1	852		4.49	20.6	7971	736		314		1160		3.7
DC2	856		4.04	16.5	8256	315		318		411		3.5
DC3	849		4.11	6.9	6293	650		349		1623		3.4
DC4	850		3.77	9.6	6142	197		338		1277		3.3
DC5	849		5.71	-1.2	3893	534		288		1007		3.3
DC6	847		4.86	4.6	3675	141		268		1397		3.6
DC7	852		2.57	-1.6	9766	1478		368		1081		3.3
DC8	854		3.15	9.8	8760	952		319		1075		3.5
DC9	850		3.29	2.0	6595	992		493		672		3.3
DC10	851		2.84	-0.3	6746	819		339		1199		3.3
DC11	854		3.04	-6.1	4095	1859		622		367		3.6
DC12	860		3.33	0.1	3843	782		543		247		3.5
DC14	849		4.43	19.1	8072	251		366		504		3.0
DC15	852		3.42	2.3	6578	1235		332		910		3.7
DC16	849		3.90	11.4	6041	309		291		1430		3.4
DC17	850		4.64	-1.2	3893	554		395		573		3.0
DC18	849		3.77	3.7	3709	283		284		1098		3.5
DC20	851		2.02	12.6	5974	599		419		1670		3.6
DC21	850		4.06	3.1	6528	591		404		842		3.4
DC22	849		3.30	7.5	6259	582		335		1530		3.7
DC23	850		4.10	10.8	6075	650		359		1088		3.6
DC24	847		2.10	4.7	6427	660		412		1328		3.5
DC25	849		3.43	9.0	6175	590		397		1342		3.4
DC26	846		2.20	26.9	5303	864		372		1655		3.3
DC27	848		2.38	14.6	5873	630		266		2008		3.4
DC28	850		2.14	23.0	5471	687		213		2814		3.3
EDC1A	840		2.03	13.6	5924	122		255		1327		3.3
EDC1B	843		2.22	8.6	3541	147		234		469		3.4
EDC1C	847		2.29	39.7	4816	166		296		310		3.3
EDC2A	842		2.23	20.8	5571	634		361		1097		3.5
EDC2B	850		2.37	4.6	3675	620		464		556		3.6
9. DEVCO COAL TESTS AT SUMMERSIDE HEATING PLANT [17]:												
100% MCR	861	13.8	2.06	102.8	5579	496	112	238	35	672	211	9.7
65% MCR	845	14.8	3.04	83.1	3595	521	170	240	22	1536	298	8.2
23% MCR	768		1.96	173.9	2768	830	115	76	2	1800		

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. C MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
10. EVANS COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 85.1 [2]:												
831115	869		4.14	-21.9	8567	987	110	124	15			0.3
831122	877		1.72	-14.2	8105	1699	46	234	6			2.2
831124	865		1.80	-20.1	8918	1260	0	206	0			1.9
831213	877		3.16	-2.1	8401	728	27	213	3			3.8
831214	879		3.04	-0.8	8419	461	37	221	3			4.0
840105	835		2.47	2.0	8331	517	28	227	4			4.3
840111	835		2.55	-7.3	7168	80	0	275	0			5.2
840117	873		1.22	42.5	3353	846	23	260	3			6.5
840124	831		2.83	6.6	4551	43	3	271	6			3.7
840126	874		2.67	8.6	4585	300	47	260	8			4.6
840207	897		1.43	14.2	5864	1467	111	246	5			5.0
840215	908		2.35	-4.5	7478	2012	519	117	17			2.5
840216	837		2.70	12.3	6402	346	23	238	10			4.7
840313	858		2.77	9.7	4468	134	23	226	8			3.4
840314	915		2.89	19.3	4154	587	160	252	14			5.3
840320	879		1.75	23.2	3822	1191	30	266	3			5.5
11. EVANS COAL TESTS AT SUMMERSIDE HEATING PLANT [17]:												
100% MCR	863	12.1	3.05	128.5	6714	615	83	227	20	630	71	11.2
65% MCR	830	3.5	2.62	156.5	4520	781	56	263	36	416	46	12.2
23% MCR	817	16.3	1.37	271.4	2946	677	116	164	40	995	461	15.1
12. EVANS COAL TESTS AT SUMMERSIDE HEATING PLANT, U.S. EPA TESTS [18]:												
FULL LD.	837	34	3.7		5092					453	107	10.5
PART LD.	838	37	4.5		4656					507	114	11.1
MAX. S. CAPT.	799	86	7.2		3953					1007	114	11.6
13. BROGAN COAL TESTS AT SUMMERSIDE HEATING PLANT, [17]:												
100% MCR	844	17.4	2.52	109.7	5635	735	116	211	18	711	92	10.1
65% MCR	863	10.6	2.62	123.1	3552	735	107	201	31	748	153	10.4
23% MCR	830	17.5	1.92	229.0	2716	962	342	163	62	1081	502	13.5
14. NOVACO COAL TESTS AT SUMMERSIDE HEATING PLANT, [17]:												
100% MCR	848	16.4	1.91	106.4	4802	733	104	402	16	359	335	9.0
65% MCR	861	13.9	1.35	117.4	6951	763	159	276	45	494	113	10.4
23% MCR	825	13.6	0.68	227.8	3005	581	111	194	44	895	568	14.2

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. MEAN	STD. DEV.	C Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
15. WESTERN KENTUCKY NO.9 COAL TESTS AT QUEEN'S UNIV. QFBC. TR. 85.1 [2]:												
841108	790		3.32	15.5	7658	507	52	218	26			6.0
841112	789		4.6	9.2	8403	274	26	350	6			5.9
841115	799		2.05	13.3	7953	951	41	354	5			5.9
841119	796		1.94	11.2	8916	1030	51	314	5			5.9
16. BYRON CREEK COAL TESTS AT CCRL (MARK II), ERP/ERL 83-12 (TR) [11]:												
1	921		0	-1.0	6564	250		270		430		4.7
2	989		0	5.0	8305	200		170		500		3.9
3	816		0	-9.1	8026	220		20		1180		4.8
5	895		0	-3.2	9384	300		260		900		3.7
6	897		0	-2.6	5710	250		200		1020		3.8
7	1010		0	-5.9	5258	240		340		790		4.1
8	1015		0	6.7	4736	240		280		1460		3.7
9	1002		0	-7.4	7156	300		300		690		4.0
10	1009		0	9.2	6076	370		270		310		3.8
13	911		0	19.9	6041	290		220		700		4.2
14	987		0	18.3	7504	250		270		120		3.8
15	811		0	-11.6	6598	290		250		680		4.2
16	802		0	-0.9	6128	240		130		970		3.8
17	791		0	-6.8	8061	350		160		340		3.8
18	897		0	18.3	7695	320		230		240		4.0
19	824		0	-5.5	10359	350		260		1080		4.5
20	797		0	15.0	8670	340		160		170		3.9

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. C MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
17. LINE CREEK COAL TASTS AT CCRL (MARK I), ERP/ERL 81-32 (TR) [9]:												
1	1070		0	33.9	5625	176		280		170		4.9
2	1020		0	39.5	5435	158		240		310		4.4
3	921		0	29.4	5895	140		220		420		5.0
4	1080		0	39.6	6734	140		340		340		5.6
5	910		0	57.4	3622	130		240		460		7.2
6	987		0	39.0	5529	155		310		300		5.9
7	948		0	28.7	5799	166		180		200		5.4
8	1074		0	58.7	5292	158		190		190		5.7
9	999		0	41.3	5940	194		90		220		5.1
10	897		0	24.3	6116	206		120		330		5.3
11	1101		0	38.8	7628	138		230		230		4.9
12	997		0	23.4	8319	144		220		210		5.0
13	900		0	23.1	7871	147		150		300		5.2
14	911		0	16.6	3297	118		80		1750		5.3
15	941		0	40.7	3421	115		190		160		4.6
16	799		0	16.6	5898	126		70		410		5.5
17	691		0	17.8	5717	107		50		540		5.5
18	905		0	17.4	9243	171		130		410		4.9
20	1011		0	43.5	7829	147		280		240		5.2
21	989		0	66.8	5393	138		260		160		5.3
22	1001		0	67.7	5128	160		200		170		5.3
23A	989		0	35.3	5846	140		160		230		5.1
23B	990		0	34.4	5840	140		160		240		5.1
23C	987		0	38.3	5887	150		150		220		4.8

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. C MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
18. HIGHVALE COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 87.3 [3]:												
860416	749		0	23.7	4858	23	6	194	11	380		4.1
860415	751		0	34.1	4892	38	1	253	2	180		4.7
860418	798		0	21.1	4834	33	2	187	4	590		3.2
860409	847		0	-1.7	4358	200	14	120	7	7210		1.7
860408	847		0	54.6	4428	1	1	344	2	560		7.6
860417	850		0	23.8	5892	50	3	220	2	100		4.0
860407	951		0	30.4	5938	54	2	275	2	570		4.6
19. HIGHVALE COAL TESTS AT CCRL (MARK I), ERP/ERL 81-36 (J) [10]:												
1	760		0	24.0	2985	47		100		150		5.0
2	759		0	2.6	3220	56		95		200		2.5
3	863		0	24.5	2889	106		170		100		5.0
4	862		0	15.6	2996	115		150		50		2.6
5	935		0	20.5	3044	124		200		50		4.7
6	949		0	25.9	2879	150		170		50		2.3
7	954		0	9.2	6013	138		280		75		5.0
8	948		0	8.1	6397	142		180		50		7.5
9	857		0	13.4	5784	104		210		100		4.7
10	857		0	0.5	6605	113		190		75		2.6
11	754		0	16.9	5662	42		135		50		5.2
12	759		0	9.7	5800	57		100		100		2.6
13	953		0	8.4	9532	271		285		50		4.9
14	954		0	6.5	9798	167		230		100		2.2
15	852		0	12.8	10161	71		235		120		5.0
16	856		0	-0.6	10038	136		180		75		2.6
17	756		0	14.1	9713	53		160		100		5.2
18	761		0	8.1	9505	58		165		100		2.5
20. HIGHVALE COAL TESTS IN CIRCULATING FBC AT UBC, CONTRACT 52SS. 23440-7-9136 [21]:												
RUN9-1	755		0	12.1	27048	12		54		320		2.3
RUN9-2	756		0	16.4	27136	28		74		330		3.0
RUN10-1	754		0	20.3	26167	8		106		397		3.6
RUN10-2	762		0	18.3	26079	8		101		481		3.3
RUN11-1	865		0	17.7	22819	6		203		34		3.2
RUN11-2	894		0	16.4	25726	12		208		24		3.0
RUN12-1	880		0	17	22819	0		215		24		3.1
RUN12-2	881		0	16.4	26872	0		195		19		3.0

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. C MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
21. WASHED MT KLAPPAN COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 87.4 [4]:												
860113	936		0	-4.5	7234	204	32	347	17			4.9
860122	933		0	-11.0	3706	178	5	165	17			2.4
860127	896		0	9.8	3883	51	13	375	15			5.8
22. MT KLAPPAN COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 87.4 [4]:												
860114	933		0	-5.7	8221	272	24	266	16			2.8
860120	936		0	-1.4	6234	402	8	247	11			4.2
860121	924		0	-4.5	5686	239	34	122	33			2.7
23. MT KLAPPAN COAL TESTS IN CIRCULATING FBC AT UBC, CONTRACT 52SS. 23440-7-9136 [21]:												
RUN14-1	859		0	15.2	22026	-		69		225		2.8
RUN14-2	863		0	12.7	22146	99		62		391		2.4
RUN14-3	872		0	15.2	21665	148		93		547		2.8
RUN14-4	864		0	19.7	16128	237		100		134		3.5
RUN14-5	870		0	17.7	16730	-		100		115		3.2
RUN7-1	849		0	28.4	22508	-		196		658		4.7

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. C MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
24. ONAKAWANA LIGNITE TEST AT CCRL (MARK I), ERP/ERL 81-30 (CF) [8]:												
1	814	25	0	47.0	5129	663	194	130	26	571	395	5.8
2	850	7	0	33.2	5868	701	97	93	13	921	596	4.0
3	757	13	0	32.7	5779	532	86	70	12	1083	680	4.2
4	938	6	0	46.2	6080	1288	48	88	11	2125	629	4.1
5	841	19	0	50.2	5403	1071	138	85	35	2425	2724	3.9
6	754	9	0	35.9	5226	608	285	430	6	1367	634	4.2
7	943	6	0	38.0	7708	1142	86	138	19	1383	833	3.9
8	831	34	1.62	24.6	6518	229	213	71	33	2810	327	4.2
25. ONAKAWANA LIGNITE TESTS AT CCRL MARK (II), ERP/ERP 87-67 (OPJ) [15]:												
1	900	9	0	32.8	5225	840	185	211	21	655	344	4.2
2	900	10	0	21.3	5722	725	179	206	25	579	416	3.7
3	804	6	0	15.6	6559	503	125	200	8	652	373	3.9
4	800	11	0	15.7	6557	316	94	211	16	460	173	4.1
5	852	5	1.20	9.9	6599	592	193	145	20	998	609	3.9
6	847	10	1.28	17.9	6153	378	148	130	30	610	540	3.7
7	809	12	1.45	41.8	4935	500	203	159	25	1382	116	4.1
8	807	20	0	1.9	4787	752	445	160	31	2750	2005	5.0
9	904	11	0	21.2	5526	809	405	202	39	886	825	4.7
26. POPLAR RIVER LIGNITE TESTS IN CIRCULATING FBC AT UBC, CONTRACT 52SS.23440-7-9136 [21]:												
RUN15-1	872		0	18.5	23177	3		145		51		3.3
RUN15-2	877		0	17.8	24406	0		140		54		3.2
RUN15-3	801		0	21.9	19841	25		113		98		3.8
RUN15-4	881		0	18.5	23879	22		147		54		3.3
27. WASHERY REJECT TESTS AT CCRL (MARK II), ERP/ERL 87-71 [16]:												
PRB1	855		0	6.5	7117	4729		478		387		4.6
PRB2	841		0	4.4	6599	4368		415		795		3.5
PR1	841		2.84	-0.4	3396	670		426		663		3.4
PR2	844		3.11	2.9	3381	268		441		448		4.2
PR3	846		2.97	-5.9	6459	892		345		757		3.5
PR4	852		3.61	-10.5	6528	259		325		879		3.1
PR5	851		2.94	-3.7	6529	919		333		689		4.1
PR5A	824		4.13	-6.5	6495	1324		357		1897		3.9
PR6	852		4.56	5.1	6816	801		404		46		4.0
PR7	850		2.65	-14.9	4855	633		339		609		2.9
PR8	841		3.33	-16.1	4853	367		341		549		3.5
PR9	850		4.61	18.3	4094	699		442		45		5.6

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
28. SYNCRUDE COKE TESTS AT QUEEN'S UNIV. QFBC. TR. 85.1 [2]:												
840605	1047		3.38	4.5	2301	861	181	829	13	290		0.9
840612	1064		2.07	7.1	3176	1078	135	758	36	275		3.8
840618	967		1.73	-17.7	3462	562	32	504	10	250		1.7
840703	1061		2.06	-13.5	2986	1937	128	750	15	200		2.5
840731	1039		2.45	-14.4	3271	1333	82	559	6	300		0.6
840814	966		2.90	-16.5	2872	1304	258	633	28	300		1.3
840820	1036		1.85	-28.2	2796	1773	120	498	5	200		0.8
840827	1105		1.94	-19.6	2910	6577	94	262	-	1925		0.4
840911	1089		2.83	-13.3	3309	2757	167	546	14	300		0.9
29. SYNCRUDE COKE TESTS AT CCRL (MARK II), ERP/ERL 86-74 (TR) [13]:												
BSC1	841		0	-19.8	3920	4294	889	250	31	1245	1233	3.8
BSC2	786		0	55.6	1966	2554	118	240	18	385	59	6.5
BSC3	841		0	-15.5	2951	4445	65	477	21	322	63	4.0
SC1	933		3.75	6.8	2461	346	60	792	25	469	107	5.3
SC2	843		4.68	-23.2	3175	259	15	776	23	359	113	3.0
SC3	830		2.04	13.7	2029	1116	36	552	20	430	63	2.6
SC4	826		1.12	-28.8	3991	2389	196	414	23	1499	371	2.6
30. SYNCRUDE COKE TESTS IN CIRCULATING FBC AT KARHULA, FINLAND [20]:												
1	823		0	13.8	11940	4300		100		650		3.6
2	890		0	16.0	11064	4800		150		110		3.2
3	940		0	21.9	12637	5000		520		80		3.8
4	937		2.04	30.8	12030	480		310		50		4.7
5	881		1.54	19.3	12875	500		130		70		3.2
6	854		2.26	18.0	12597	480		200		90		3.4
7A	833		2.11	20.5	11522	460		160		120		3.5
8A	884		1.71	28.5	12209	490		120		40		4.5
7B	842		1.64	32.8	11244	470		175		30		5.0
8B	896		1.65	28.3	11890	480		185		45		4.3
9	938		1.72	19.8	12527	490		245		40		3.2
10	947		1.73	21.3	13472	470		240		20		3.5
11	960		1.76	24.1	14109	430		450		5		4.0
12	883		1.34	29.5	8477	490		70		20		4.8
13	882		1.41	31.1	8020	440		65		10		5.0
14	862		1.21	21.8	7110	580		54		45		3.6
15	875		1.03	18.4	6430	520		97		50		3.2
16	900		1.53	23.9	12020	480		220		10		4.0

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. C MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
31. SUNCOR COKE TESTS AT CCRL (MARK I), ERP/ERL 81-27 (TR) [7]:												
2	808		0	7.1	5546	1330		100	-	411	87	3.9
6	856		0	-6.8	7562	3740		85	-	233	33	2.6
7	858		0	7.1	8066	3355		90	31	291	52	-
8	760		0	1.0	5546	3875		21	4	210	208	2.8
9	757		0	-20.5	8138	4320		24	2	643	53	2.3
10	759		0	7.2	7706	3505		23	3	260	141	4.9
11	956		0	2.8	5762	2240		19	-	8	5	2.4
21	957		0	19.2	3313	2890		442	87	188	416	2.6
22	954		0	38.8	2881	2330		461	39	188	23	5.1
23	850		3.00	32.5	5834	702		43	8	203	26	4.5
32. SASKATCHEWAN PETROLEUM COKE TESTS AT QUEEN'S UNIV., QFBC. TR. 87.5 [5]:												
860212	833		0	-9.9	3968	365	34	154	21	830		5.1
860303	852		0	-9.1	5037	1656	49	157	7	1650		1.0
860305	905		0	-7.7	5509	1383	29	238	4	1380		2.8
860304	904		0	6.1	5222	1583	18	302	2	520		2.3
860310	906		0	10.9	4297	887	62	304	7	550		5.8
860311	905		0	-6.8	4235	1734	339	238	17	600		3.7
860218	953		0	-14.8	4749	1225	20	331	3	480		3.5
860219	953		0	-1.3	5386	1823	74	285	12	1600		1.6
860226	948		0	15.2	4173	1347	54	378	3	550		3.8
860224	1005		0	5.4	4091	1544	22	368	3	500		3.7
860225	1005		0	12.7	4214	1685	53	416	4	570		3.1
860317	901		1.97	2.7	5098	840	7	233	20	500		3.3
860318	852		1.84	-0.5	4872	1196	30	252	3	1550		1.7
860324	900		4.08	-0.2	5283	961	27	197	30	1130		1.9

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
33. COAL/WATER SLURRY TESTS AT QUEEN'S UNIV., QFBC. TR. 87.6 [6]:												
870621	852		0	27.9	3044			310		1300		
870922	852		0	41.1	2302			270		700		
870914	909		0	28.7	2942	778	44	369	7	420		4.1
870916	903		0	24.1	3121	545	55	160	39	400		4.4
870915	955		0	18.1	3492			60		1600		
870921	956		0	17.3	3223	373	22	237	6	1620		4.0
870710	860		0	33.4	3453	947	24	365	4	400		5.9
870713	853		3	17.8	4412	240	31	290	17	700		3.4
870714	852		1.4	34.4	3914	213	6	438	5	280		6.5
870629	909		0	24.7	3786	910	38	239	42	200		4.3
870707	909		0	17.8	3479			332		800		
870813	968		0	15.6	4528	783	33	78	1	3180		3.5
870729	868		0	56.8	4106	353	88	323	18	1120		8.1
870728	908		0	51.9	4297			325		1200		
870721	954		0	47.9	4464			395		200		
870723	951		4.18	45.1	4438	576	24	377	4	300		6.2
870722	956		0	35.4	4924	954	4	368	4	720		5.7
34. NO.6 OIL TESTS AT CCRL (MARK II) ERP/ERL 87-22 (CF) [14]:												
OIL01	609		0	8.1	5868	1315		94		3127		8.2
OIL02	959		0	14.3	6283	1340		146		775		3.5
OIL03	858		0	11.1	5813	1252		168		901		5.9
OIL04	851		0	9.5	6366	1213		231		229		4.2
OIL05	852		5.98	17.9	6090			222		284		3.7
OIL06	855		6.93	35.7	5259	256		198		154		3.3
OIL07	844		0	30.3	6090	1180		177		1071		4.1
OIL08	806		0	46.0	5619	1297		144		1919		3.4
OIL09	829		5.7	32.0	5813			135		611		3.9
OIL10	845		5.7	28.2	5813			127		1463		4.2
OIL11	827		5.98	27.1	5536			139		757		3.8
OIL12	825		6.36	29.9	5204			125		820		5.1
OIL13	855		4.73	28.9	5813	148		144		502		3.9
OIL14	846		3.46	34.5	5259	238		148		683		3.9
OIL15	845		0	40.0	5259	856		131		808		3.9
OIL16	854		0	46.0	3045	1238		116		177		3.4
OIL17	853		2.99	39.3	3322			137		183		3.2
OIL18	852		3.23	63.2	3072			145		127		3.6
OIL19	856		4.35	60.0	3045			145		143		3.5
OIL20	852		2.83	54.1	3045	298		156		159		4.0
OIL21	845		3.19	43.0	4982			138		1361		3.8
OIL22	842		3.59	56.1	4706			131		959		3.9

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. MEAN	BED TEMP. STD. DEV.	C Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	SO2 (ppm) STD. DEV.	NOx (ppm) MEAN	NOx (ppm) STD. DEV.	CO (ppm) MEAN	CO (ppm) STD. DEV.	O2 IN FLUE GAS, %
35. CANMET PITCH TESTS AT CCRL (MARK II), ERP/ERL 87-22 (CF) [14]:												
CP1	890		0	13.7	5979	1579		254		373		3.4
CP1A	849		0	28.2	5712	1558		245		293		3.8
CP2	847		3.38	35.4	5285			164		644		3.7
CP2A	852		3.19	26.1	5605			165		558		3.6
CP2B	851		3.66	44.0	4884			163		1597		3.9
CP2C	846		3.62	44.4	4938			201		1681		4.2
CP2D	839		4.01	22.2	5898	388		193		1949		4.1
CP9	850		4.23	15.3	5738			171		1242		4.0
CP9A	849		4.22	36.6	5338			195		857		3.8
CP9C	851		4.14	33.8	5445			183		1900		3.6
CP9D	842		3.89	35.1	5792			166		2323		3.7
CP9E	842		3.8	28.0	5925	310		172		2325		3.5
CP7	843		3.97	21.1	8114	223		227		2260		3.6
36. CANMET PITCH TESTS IN CIRCULATING FBC AT UBC, CONTRACT 24St. 23440-6-9007 [19]:												
1	847		1.7	2.3	26986	382		165				3.8
2	895		1.5	0.3	27332	291		140		800		3.4
3	901		2.3	-2.2	26813	404		135		1000		3.0
4	905		2.3	2.0	19202	254		157		700		3.8
37. CANMET PITCH TESTS IN CIRCULATING FBC AT UBC, CONTRACT 52SS. 23440-7-9136 [21]:												
RUN17-B	888		0	17.3	25602	1261		155		179		3.2
RUN17-1	895		2.5	16.0	26121	225		165		120		3.0
RUN17-2	875		2.5	19.2	24218	209		193		145		3.5
RUN17-4	877		1.3	30.4	22488	532		232		278		5.0
RUN17-5	875		3.9	21.1	24218	323		272		431		3.8
RUN17-6	880		3.9	21.9	23180	333		263		157		3.9

TABLE 3 TESTING CONDITIONS AND RESULTS OF MEASUREMENTS (CONT.)

TEST NO.	BED TEMP. C MEAN	STD. DEV.	Ca/S RATIO	EXCESS OXYGEN %	FUEL FIRING MJ/m2h	SO2 (ppm) MEAN	STD. DEV.	NOx (ppm) MEAN	STD. DEV.	CO (ppm) MEAN	STD. DEV.	O2 IN FLUE GAS, %
38. H-OIL PITCH TESTS IN CIRCULATING FBC AT UBC, CONTRACT 24St.23440-6-9007 [19]:												
1	855		0.54	-0.2	25914	845		105				2.4
2	822		0.68	9.4	26801	677		125				3.7
3	894		1.2	9.3	26446	204		100				3.6
39. H-OIL PITCH TESTS IN CIRCULATING FBC AT UBC, CONTRACT 52SS. 23440-7-9136 [21]:												
RUN18-B	893		0	19.8	25733	1332		221		150		3.6
RUN18-C	881		3.5	17.2	18457	374		178		124		3.2
RUN20-B	760		0	17.2	24669	1052		126		168		3.2
RUN20-2	873		2.6	19.1	23959	656		237		144		3.5
RUN20-3	884		5.6	22.5	23959	285		295		217		4.0
RUN20-4	904		4.5	20.5	24846	463		281		164		3.7
40. BITUMEN TESTS AT CCRL (MARK II), ERP/ERL 87-22 (CF) [14]:												
BIT1	841		1.28	16.4	3228			108		955		3.4
BIT2	837		3.45	63.0	2867			119		532		7.5
BIT4	847		2.68	4.1	4922	923		137		6880		4.9

TABLE 4 SUMMARY OF EMISSION DATA

TEST NO.	NO EMISSION NG/J MEAN	NG/J STD.DEV.	NO EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	NG/J STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.
1. MINTO COAL TESTS AT QUEEN'S UNIV., QFBC. TR.83.1 [1]:									
821116	75.5		0.176		12.2	1677		3.90	
830106	84.3		0.196		13.6	1872		4.36	
830112	64.2		0.149		10.4	1644		3.82	
830124	85.4		0.199		13.8	1226		2.85	
830126	136.8		0.318		22.1	0		0.00	
830127	129.8		0.302		20.9	346		0.81	
830201	84.9		0.197		13.7	497		1.16	
830202	95.7		0.223		15.4	129		0.30	
830215	120.7		0.281		19.5	1039		2.42	
830216	126.5		0.294		20.4	710		1.65	
830217	148.0		0.344		23.9	640		1.49	
830218	148.4		0.345		23.9	2487		5.79	
830224	146.1		0.340		23.6	1131		2.63	
830225	138.8		0.323		22.4	1176		2.74	
830226	104.9		0.244		16.9	646		1.50	
830322	111.1		0.258		18.8	985		2.29	
830324	88.6		0.206		15.0	1345		3.13	
830329	131.2		0.305		22.3	129		0.30	
830330	84.4		0.196		14.4	172		0.40	
2. MINTO COAL TESTS AT CCRL (MARK I), ERP/ERL 81-36(J) [10]:									
7	76.9		0.179		12.9	4260		9.91	
8	60.6		0.141		10.2	4275		9.95	
9	29.3		0.068		4.9	4112		9.57	
10	16.3		0.038		2.7	4209		9.79	
11	67.1		0.156		11.3	4085		9.50	
12	58.7		0.137		9.9	4065		9.46	
13	18.6		0.043		3.1	3827		8.90	
14	7.1		0.017		1.2	3881		9.03	
15	3.0		0.007		0.5	4110		9.56	
16	3.7		0.009		0.6	4094		9.52	
17	22.2		0.052		3.7	5127		11.92	
18	7.7		0.018		1.3	5018		11.67	
A1	7.8		0.018		1.3	1260		2.93	
A2	41.7		0.097		3.3	1489		3.46	
A3	62.9		0.146		10.6	493		1.15	
A4	47.4		0.110		8.0	570		1.32	
A5	86.5		0.201		14.6	60		0.14	
A6	66.1		0.154		11.1	110		0.25	

TABLE 4 SUMMARY OF EMISSION DATA (CON'T)

TEST NO.	NO EMISSION NG/J MEAN	NG/J STD.DEV.	NO EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	NG/J STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV
3. MINTO COAL TESTS AT SUMMERSIDE HEATING PLANT [17]:									
100% MCR	245.4	59.3	0.571	0.138	34.4	984	167	2.29	0.387
65% MCR	178.0	28.3	0.414	0.066	22.3	998	165	2.32	0.385
23% MCR	113.1	41.3	0.263	0.096	14.3	1651	409	3.84	0.951
4. MINTO COAL TESTS IN CIRCULATING FBC AT UBC,CONTRACT 24ST 23440-6-9007 [19]									
1	45.0		0.105		8.2	1356		3.15	
2	52.2		0.121		9.5				
3	44.1		0.103		8.1				
4	50.9		0.118		9.3				
5	53.1		0.123		9.7				
6	54.5		0.127		10.0				
7	41.8		0.097		7.6	1243		2.89	
8	47.7		0.111		8.7	915		2.13	
9	51.8		0.121		9.4	571		1.33	
5. MINTO COAL TESTS IN CIRCULATING FBC AT UBC,CONTRACT 52SS 23440-7-9136 [21]:									
RUN3-C1	47.4		0.110		7.7	485		1.13	
RUN16-1	104.7		0.244		17	46		0.11	
RUN16-2	88.3		0.205		14.3	44		0.10	
RUN16-3	76.1		0.177		12.3	653		1.52	
RUN16-4	109.3		0.254		17.7	975		2.27	
RUN16-5	81.9		0.191		13.3	480		1.12	
RUN16-6	71.8		0.167		11.7	443		1.03	
6. DEVCO COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 83.1 [1]:									
830309	179.9		0.418		18.3	702		1.63	
830310	149.6		0.348		15.2	1196		2.78	
830315	199.9		0.465		20.3	468		1.09	
830316	188.0		0.437		19.1	1163		2.71	
7. DEVCO COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 85.1 [2]:									
841127	178.1	1.7	0.414	0.004	17.1	665	43	1.55	0.101
841204	144.8	2.6	0.337	0.006	13.9	361	30	0.84	0.069
841218	131.2	2.3	0.305	0.005	12.6	775	36	1.80	0.085
841219	132.8	2.0	0.309	0.005	12.8	748	41	1.74	0.096
850107	126.9	2.4	0.295	0.006	12.2	508	22	1.18	0.051
850115	164.7	2.6	0.383	0.006	18.0	1058	57	2.46	0.133
850129	275.0	2.3	0.640	0.005	30.0	541	24	1.26	0.057
850304	116.5		0.271		12.7				

TABLE 4 SUMMARY OF EMISSION DATA (CON'T)

TEST NO.	NO EMISSION NG/J MEAN	NO EMISSION NG/J STD.DEV.	NO EMISSION lb/10^6Btu MEAN	NO EMISSION lb/10^6Btu STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	SO2 EMISSION NG/J STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	SO2 EMISSION lb/10^6Btu STD. DEV
8. DEVCO COAL TESTS AT CCRL (MARK II), ERP/ERL 85-44 (OPJ) [12]:									
BDC1	159.0		0.370		13.8	3148		7.32	
BDC2	160.4		0.373		13.9	3253		7.57	
BDC3	131.9		0.307		11.4	3090		7.19	
BDC4	149.2		0.347		12.9	2766		6.44	
BDC5	151.3		0.352		13.1	3241		7.54	
DC1	132.7		0.309		11.5	664		1.54	
DC2	129.3		0.301		11.2	273		0.64	
DC3	130.3		0.303		11.3	518		1.20	
DC4	129.0		0.300		11.2	160		0.37	
DC5	100.1		0.233		8.7	396		0.92	
DC6	98.1		0.228		8.5	110		0.26	
DC7	125.5		0.292		10.9	1075		2.50	
DC8	121.8		0.283		10.6	775		1.80	
DC9	174.9		0.407		15.2	751		1.75	
DC10	117.2		0.273		10.2	604		1.40	
DC11	202.9		0.472		17.6	1293		3.01	
DC12	188.8		0.439		16.4	580		1.35	
DC14	152.5		0.355		13.2	223		0.52	
DC15	118.3		0.275		10.2	939		2.18	
DC16	113.0		0.263		9.8	256		0.60	
DC17	136.5		0.317		11.8	408		0.95	
DC18	102.5		0.238		8.9	218		0.51	
DC20	163.3		0.380		14.2	498		1.16	
DC21	145.3		0.338		12.6	453		1.05	
DC22	125.3		0.291		10.9	464		1.08	
DC23	138.9		0.323		12.0	537		1.25	
DC24	149.0		0.347		12.9	509		1.18	
DC25	150.6		0.350		13.0	477		1.11	
DC26	163.9		0.381		14.2	624		1.45	
DC27	105.7		0.246		9.2	534		1.24	
DC28	90.9		0.211		7.9	626		1.46	
EDC1A	100.2		0.233		8.7	102		0.24	
EDC1B	87.9		0.204		7.6	118		0.27	
EDC1C	143.8		0.334		12.5	172		0.40	
EDC2A	151.3		0.352		13.1	567		1.32	
EDC2B	168.2		0.391		14.6	479		1.12	
9. DEVCO COAL TESTS AT SUMMERSIDE HEATING PLANT [17]:									
100% MCR	163.2	24.0	0.380	0.056	16.4	726	164	1.69	0.381
65% MCR	147.6	13.5	0.343	0.031	14.4	684	223	1.59	0.519
23% MCR	70.3	1.9	0.164	0.004	7.0	1638	227	3.81	0.528

TABLE 4 SUMMARY OF EMISSION DATA (CON'T)

TEST NO.	NO EMISSION NG/J MEAN	NG/J STD.DEV.	NO EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	NG/J STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV
10. EVANS COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 85.1 [2]:									
831115	33.7	4.1	0.078	0.009	4.0	573	64	1.33	0.149
831122	68.8	1.8	0.160	0.004	8.0	1066	29	2.48	0.067
831124	56.3	0.0	0.131	0.000	6.8	735	0	1.71	0.000
831213	72.4	1.0	0.168	0.002	8.0	528	20	1.23	0.046
831214	76.1	1.0	0.177	0.002	8.4	339	27	0.79	0.063
840105	81.9	1.4	0.191	0.003	9.0	398	22	0.93	0.050
840111	90.1	0.0	0.210	0.000	10.1	56	0	0.13	0.000
840117	133.6	1.5	0.311	0.004	14.7	927	25	2.16	0.059
840124	102.6	2.3	0.239	0.005	11.5	35	2	0.08	0.006
840126	100.0	3.1	0.233	0.007	11.2	246	39	0.57	0.090
840207	98.4	2.0	0.229	0.005	10.9	1251	95	2.91	0.220
840215	39.2	5.7	0.091	0.013	4.4	1438	371	3.35	0.863
840216	94.2	4.0	0.219	0.009	10.4	292	19	0.68	0.045
840313	86.2	3.1	0.201	0.007	9.4	109	19	0.25	0.044
840314	104.9	5.8	0.244	0.014	11.6	521	142	1.21	0.331
840320	113.5	1.3	0.264	0.003	12.5	1084	27	2.52	0.064
11. EVANS COAL TESTS AT SUMMEREIDE HEATING PLANT [17]:									
100% MCR	168.9	14.9	0.393	0.035	16.8	892	120	2.07	0.280
65% MCR	225.2	30.8	0.524	0.072	21.9	1265	91	2.94	0.211
23% MCR	204.0	49.8	0.475	0.116	19.3	1733	297	4.03	0.691
12. EVANS COAL TESTS AT SUMMERSIDE HEATING PLANT, U.S. EPA TESTS [18]:									
FULL LD.	266.5		0.620		29.6	258		0.60	
PART LD.	257.9		0.600		28.6	430		1.00	
MAX. S. CAPT.	300.9		0.700		33.4	26		0.06	
13. BROGAN COAL TESTS AT SUMMERSIDE HEATING PLANT [17]:									
100% MCR	146.9	12.5	0.342	0.029	14.3	1092	172	2.54	0.401
65% MCR	147.6	22.8	0.343	0.053	13.5	1152	168	2.68	0.390
23% MCR	186.3	70.9	0.433	0.165	16.1	2346	834	5.46	1.940
14. NOVACO COAL TESTS AT SUMMERSIDE HEATING PLANT [17]:									
100% MCR	279.5	11.1	0.650	0.026	23.1	1087	154	2.53	0.359
65% MCR	199.9	32.6	0.465	0.076	16.2	1179	246	2.74	0.572
23% MCR	206.7	46.9	0.481	0.109	18.4	1320	252	3.07	0.587

TABLE 4 SUMMARY OF EMISSION DATA (CONT.)

TEST NO.	NO EMISSION NG/J MEAN	NG/J STD.DEV.	NO EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	NG/J STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.
15. WESTERN KENTUCKY NO.9 COAL TESTS AT QUEEN'S UNIV. QFBC. TR. 85.1 [2]:									
841108	89.4	10.7	0.208	0.025	8.8	444	45	1.03	0.106
841112	136.3	2.3	0.317	0.005	12.6	228	22	0.53	0.050
841115	142.0	2.0	0.330	0.005	13.0	814	35	1.89	0.082
841119	123.3	2.0	0.287	0.005	11.6	863	43	2.01	0.099
16. BYRON CREEK COAL TESTS AT CCRL (MARK II), ERP/ERL 83-12 (TR) [11]:									
1	93.8		0.218		10.8	185		0.43	
2	62.7		0.146		7.2	157		0.37	
3	6.4		0.015		0.7	149		0.35	
5	88.3		0.205		10.2	217		0.51	
6	68.3		0.159		7.9	182		0.42	
7	112.1		0.261		12.9	169		0.39	
8	105.0		0.244		12.1	192		0.45	
9	97.2		0.226		11.2	207		0.48	
10	103.7		0.241		12.0	303		0.71	
13	93.0		0.216		10.7	261		0.61	
14	112.6		0.262		13.0	222		0.52	
15	77.3		0.180		8.9	191		0.44	
16	45.2		0.105		5.2	178		0.41	
17	52.2		0.122		6.0	244		0.57	
18	95.9		0.223		11.1	285		0.66	
19	86.1		0.200		9.9	247		0.57	
20	64.8		0.151		7.5	294		0.68	

TABLE 4 SUMMARY OF EMISSION DATA (CONT.)

TEST NO.	NO EMISSION NG/J MEAN	NO EMISSION NG/J STD.DEV.	NO EMISSION lb/10^6Btu MEAN	NO EMISSION lb/10^6Btu STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	SO2 EMISSION NG/J STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	SO2 EMISSION lb/10^6Btu STD. DEV.
17. LINE CREEK COAL TESTS AT CCRL (MARK I), ERP/ERL 81-32 (TR) [9]:									
1	126.6		0.294		16.9	170		0.39	
2	113.1		0.263		15.2	159		0.37	
3	96.1		0.223		12.8	130		0.30	
4	160.4		0.373		21.4	141		0.33	
5	127.9		0.297		16.9	148		0.34	
6	145.5		0.339		19.8	155		0.36	
7	78.1		0.182		11.0	154		0.36	
8	102.1		0.237		14.3	181		0.42	
9	43.0		0.100		6.0	198		0.46	
10	50.3		0.117		7.1	184		0.43	
11	107.9		0.251		15.2	138		0.32	
12	91.5		0.213		12.9	128		0.30	
13	62.2		0.145		8.8	130		0.30	
14	31.4		0.073		4.4	99		0.23	
15	90.4		0.210		12.7	117		0.27	
16	27.5		0.064		3.8	105		0.25	
17	19.8		0.046		2.8	91		0.21	
18	51.4		0.120		7.2	144		0.34	
20	135.9		0.316		17.1	152		0.35	
21	147.0		0.342		18.4	166		0.39	
22	113.7		0.264		13.5	194		0.45	
23A	73.1		0.170		10.3	136		0.32	
23B	72.6		0.169		10.2	136		0.32	
23C	70.1		0.163		9.9	150		0.35	

TABLE 4 SUMMARY OF EMISSION DATA (CONT.)

TEST NO.	NO EMISSION NG/J MEAN	NG/J STD.DEV.	NO EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	NG/J STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.
18. HIGHVALE COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 87.3 [3]:									
860416	88.0	5.0	0.205	0.012	11.4	22	6	0.05	0.014
860415	124.7	1.0	0.290	0.002	16.2	40	1	0.09	0.002
860418	83.2	1.8	0.194	0.004	10.8	31	2	0.07	0.004
860409	43.3	2.5	0.101	0.006	5.6	154	11	0.36	0.025
860408	197.4	1.1	0.459	0.003	25.6	1	1	0.00	0.003
860417	99.1	0.9	0.230	0.002	12.8	48	3	0.11	0.007
860407	131.8	1.0	0.307	0.002	17.1	55	2	0.13	0.005
19. HIGHVALE COAL TESTS AT CCRL (MARK I), ERP/ERL 81-36 (J) [10]:									
1	39.5		0.092		5.7	40		0.09	
2	31.0		0.072		4.5	39		0.09	
3	67.4		0.157		9.8	90		0.21	
4	55.2		0.128		8.0	90		0.21	
5	76.7		0.179		11.2	102		0.24	
6	68.2		0.159		9.9	128		0.30	
7	97.3		0.226		14.2	102		0.24	
8	61.9		0.144		9.0	104		0.24	
9	75.8		0.176		11.0	80		0.19	
10	60.8		0.141		8.8	77		0.18	
11	50.2		0.117		7.3	33		0.08	
12	34.9		0.081		5.1	42		0.10	
13	98.4		0.229		14.3	200		0.46	
14	78.0		0.181		11.3	121		0.28	
15	84.4		0.196		12.3	54		0.13	
16	57.0		0.132		8.3	92		0.21	
17	58.1		0.135		8.5	41		0.10	
18	56.8		0.132		8.3	43		0.10	
20. HIGHVALE COAL TESTS IN CIRCULATING FBC AT UBC, CONTRACT 52SS. 23440-7-9136 [21]:									
RUN9-1	19.7		0.046		2.8	10		0.02	
RUN9-2	28.2		0.066		3.9	23		0.05	
RUN10-1	41.6		0.097		5.8	7		0.02	
RUN10-2	39.2		0.091		5.5	6		0.01	
RUN11-1	78.0		0.181		10.9	5		0.01	
RUN11-2	79.2		0.184		11.1	10		0.02	
RUN12-1	82.2		0.191		11.5	0		0.00	
RUN12-2	74.2		0.173		10.4	0		0.00	

TABLE 4 SUMMARY OF EMISSION DATA (CONT.)

TEST NO.	NO EMISSION NG/J MEAN	NG/J STD.DEV.	NO EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	NG/J STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.
21. WASHED MT KLAPPAN COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 87.4 [4]:									
860113	120.3	5.9	0.280	0.014	15.8	151	24	0.35	0.055
860122	53.4	5.5	0.124	0.013	7.0	123	3	0.29	0.008
860127	149.4	6.0	0.347	0.014	19.6	43	11	0.10	0.026
22. MT KLAPPAN COAL TESTS AT QUEEN'S UNIV., QFBC. TR. 87.4 [4]:									
860114	63.1	3.8	0.147	0.009	11.2	138	12	0.32	0.028
860120	61.4	2.7	0.143	0.006	10.8	213	4	0.50	0.010
860121	29.3	7.9	0.068	0.018	5.2	123	17	0.29	0.041
23. MT KLAPPAN COAL TESTS IN CIRCULATING FBC AT UBC, CONTRACT 52SS. 23440-7-9136 [21]:									
RUN14-1	27.4		0.064		4.0	-		-	
RUN14-2	24.1		0.056		3.5	82		0.19	
RUN14-3	36.9		0.086		5.4	125		0.29	
RUN14-4	41.3		0.096		6.1	209		0.49	
RUN14-5	40.6		0.094		6.0	-		-	
RUN7-1	86.9		0.202		12.8	-		-	

TABLE 4 SUMMARY OF EMISSION DATA (CONT.)

TEST NO.	NO EMISSION NG/J MEAN	NG/J STD.DEV.	NO EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	NG/J STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	lb/10^6Btu STD. DEV.
24. ONAKAWANA COAL TEST AT CCRL (MARK I), ERP/ERL 81-30 (CF) [8]:									
1	65.1	13.0	0.151	0.030	7.8	708	207	1.65	0.482
2	42.1	5.9	0.098	0.014	5.1	677	94	1.58	0.218
3	31.6	5.4	0.074	0.013	3.8	512	83	1.19	0.193
4	43.8	5.5	0.102	0.013	5.3	1367	51	3.18	0.118
5	43.5	17.9	0.101	0.042	5.2	1168	151	2.72	0.350
6	198.9	2.8	0.463	0.006	24.0	600	281	1.40	0.654
7	64.8	8.9	0.151	0.021	7.8	1143	86	2.66	0.200
8	30.2	14.0	0.070	0.033	3.6	208	193	0.48	0.449
25. ONAKAWANA COAL TESTS AT CCRL MARK (II), ERP/ERP 87-67 (OPJ) [15]:									
1	95.5	9.5	0.222	0.022	11.5	811	179	1.89	0.416
2	85.0	10.3	0.198	0.024	10.2	638	158	1.48	0.367
3	78.6	3.1	0.183	0.007	9.5	422	105	0.98	0.244
4	82.8	6.3	0.193	0.015	10.0	265	79	0.62	0.183
5	54.2	7.5	0.126	0.017	6.5	472	154	1.10	0.358
6	52.1	12.0	0.121	0.028	6.3	323	127	0.75	0.294
7	77.1	12.1	0.179	0.028	9.3	517	210	1.20	0.488
8	55.3	10.7	0.129	0.025	6.7	554	328	1.29	0.763
9	83.2	16.1	0.194	0.037	10.0	711	356	1.65	0.828
26. POPLAR RIVER LIGNITE TESTS IN CIRCULATING FBC AT UBC, CONTRACT 52SS.23440-7-9136 [21]:									
RUN15-1	52.9		0.123		8.5	3		0.01	
RUN15-2	50.7		0.118		8.1	0		0.00	
RUN15-3	42.4		0.099		6.8	20		0.05	
RUN15-4	53.6		0.125		8.6	17		0.04	
27. WASHERY REJECT TESTS AT CCRL (MARK II), ERP/ERL 87-71 [16]:									
PRB1	179.9		0.418		15.1	3796		8.83	
PRB2	153.1		0.356		12.9	3437		7.99	
PR1	151.1		0.351		12.7	507		1.18	
PR2	161.8		0.376		13.6	210		0.49	
PR3	115.5		0.269		9.7	637		1.48	
PR4	103.7		0.241		8.7	176		0.41	
PR5	114.2		0.266		9.6	673		1.56	
PR5A	119.8		0.279		10.1	948		2.20	
PR6	152.7		0.355		12.8	646		1.50	
PR7	102.2		0.238		8.6	407		0.95	
PR8	101.7		0.237		8.5	233		0.54	
PR9	188.4		0.438		15.8	635		1.48	

TABLE 4 SUMMARY OF EMISSION DATA (CONT.)

TEST NO.	NO EMISSION NG/J MEAN	STD.DEV.	NO EMISSION lb/10^6Btu MEAN	STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	STD. DEV.
28. SYNCRUDE COKE TESTS AT QUEEN'S UNIV. QFBC. TR. 85.1 [2]:									
840605	322.4	5.1	0.750	0.012	23.8	714	150	1.66	0.349
840612	297.9	14.1	0.693	0.033	21.3	904	113	2.10	0.263
840618	152.0	3.0	0.354	0.007	11.8	362	21	0.84	0.048
840703	236.6	4.7	0.550	0.011	17.5	1304	86	3.03	0.200
840731	176.0	1.9	0.409	0.004	13.3	895	55	2.08	0.128
840814	195.3	8.6	0.454	0.020	13.5	858	170	2.00	0.395
840820	130.8	1.3	0.304	0.003	9.5	993	67	2.31	0.156
840827	78.1	-	0.182	-	5.0	4180	60	9.72	0.139
840911	175.0	4.5	0.407	0.010	13.0	1885	114	4.39	0.266
29. SYNCRUDE COKE TESTS AT CCRL (MARK II), ERP/ERL 86-74 (TR) [13]:									
BSC1	69.3	8.6	0.161	0.020	4.3	2538	525	5.90	1.222
BSC2	130.2	9.8	0.303	0.023	8.3	2956	137	6.88	0.318
BSC3	139.4	6.1	0.324	0.014	8.6	2772	41	6.45	0.094
SC1	298.6	9.4	0.695	0.022	18.3	278	48	0.65	0.112
SC2	212.3	6.3	0.494	0.015	12.9	151	9	0.35	0.020
SC3	219.8	8.0	0.511	0.019	15.1	948	31	2.21	0.071
SC4	102.3	5.7	0.238	0.013	7.2	1260	103	2.93	0.240
30. SYNCRUDE COKE TESTS IN CIRCULATING FBC AT KARHULA, FINLAND [20]:									
1	39.4		0.092		3.8	3617		8.41	
2	60.3		0.140		5.7	4118		9.58	
3	220.0		0.512		20.9	4513		10.50	
4	141.2		0.329		13.4	467		1.09	
5	53.9		0.125		5.1	442		1.03	
6	82.3		0.191		7.8	421		0.98	
7A	67.2		0.156		6.4	412		0.96	
8A	53.7		0.125		5.1	467		1.09	
7B	80.8		0.188		7.7	463		1.08	
8B	82.6		0.192		7.9	457		1.06	
9	102.1		0.237		9.7	436		1.01	
10	101.3		0.236		9.6	423		0.98	
11	194.2		0.452		18.5	396		0.92	
12	31.5		0.073		3.0	470		1.09	
13	29.6		0.069		2.8	427		0.99	
14	22.8		0.053		2.2	523		1.22	
15	39.8		0.093		3.8	455		1.06	
16	94.7		0.220		9.0	441		1.03	

TABLE 4 SUMMARY OF EMISSION DATA (CONT.)

TEST NO.	NO EMISSION NG/J MEAN	NO EMISSION NG/J STD.DEV.	NO EMISSION lb/10^6Btu MEAN	NO EMISSION lb/10^6Btu STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	SO2 EMISSION NG/J STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	SO2 EMISSION lb/10^6Btu STD. DEV.
31. SUNCOR COKE TESTS AT CCRL (MARK I), ERP/ERL 81-27 (TR) [7]:									
2	35.7	-	0.083	-	3.9	1013		2.36	
6	26.3	-	0.061	-	2.9	2473		5.75	
7	32.1	11.1	0.075	0.026	3.5	2556		5.95	
8	7.1	1.3	0.016	0.003	0.8	2782		6.47	
9	6.3	0.5	0.015	0.001	0.7	2426		5.64	
10	8.2	1.1	0.019	0.002	0.9	2673		6.22	
11	6.5	-	0.015	-	0.7	1636		3.81	
21	176.1	34.7	0.410	0.081	19.2	2457		5.72	
22	214.5	18.1	0.499	0.042	23.3	2312		5.38	
23	19.2	3.6	0.045	0.008	2.1	669		1.56	
32. SASKATCHEWAN PETROLEUM COKE TESTS AT QUEEN'S UNIV., QFBC. TR. 87.5 [5]:									
860212	50.1	6.8	0.117	0.016	8.5	253	24	0.59	0.055
860303	51.8	2.3	0.121	0.005	8.7	1166	35	2.71	0.080
860305	79.6	1.3	0.185	0.003	13.3	987	21	2.30	0.048
860304	116.9	0.8	0.272	0.002	19.5	1308	15	3.04	0.035
860310	123.3	2.8	0.287	0.007	16.7	768	54	1.79	0.125
860311	104.8	7.5	0.244	0.017	13.4	1629	319	3.79	0.741
860218	102.0	0.9	0.237	0.002	20.2	806	13	1.87	0.031
860219	102.7	4.3	0.239	0.010	17.0	1401	57	3.26	0.132
860226	159.3	1.3	0.371	0.003	26.2	1211	49	2.82	0.113
860224	141.3	1.2	0.329	0.003	23.5	1265	18	2.94	0.042
860225	171.7	1.7	0.399	0.004	28.6	1483	47	3.45	0.109
860317	94.2	8.1	0.219	0.019	18.6	725	6	1.69	0.014
860318	99.0	1.2	0.231	0.003	14.5	1004	25	2.34	0.059
860324	78.0	11.9	0.181	0.028	11.5	812	23	1.89	0.053

TABLE 4 SUMMARY OF EMISSION DATA (CONT.)

TEST NO.	NO EMISSION NG/J MEAN	STD.DEV.	NO EMISSION lb/10^6Btu MEAN	STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	STD. DEV.
33. COAL/WATER SLURRY TESTS AT QUEEN'S UNIV., QFBC. TR. 87.6 [6]:									
870621	143.5		0.334		15.7				
870922	137.2		0.319		15.2				
870914	171.8	3.3	0.400	0.008	18.2	773	44	1.80	0.102
870916	76.3	18.6	0.177	0.043	7.8	554	56	1.29	0.130
870915	23.3		0.054		2.8				
870921	122.6	3.1	0.285	0.007	11.0	412	24	0.96	0.056
870710	199.2	2.2	0.463	0.005	19.2	1103	28	2.57	0.065
870713	125.0	7.3	0.291	0.017	13.5	221	28	0.51	0.066
870714	212.7	2.4	0.495	0.006	23.0	221	6	0.51	0.014
870629	107.4	18.9	0.250	0.044	11.8	872	36	2.03	0.085
870707	156.3		0.364		16.5				
870813	32.4	0.4	0.075	0.001	3.5	694	29	1.61	0.068
870729	183.5	10.2	0.427	0.024	20.1	428	107	0.99	0.248
870728	178.8		0.416		19.5				
870721	209.0		0.486		23.1				
870723	204.0	2.2	0.475	0.005	21.5	665	28	1.55	0.064
870722	173.6	1.9	0.404	0.004	19.7	960	4	2.23	0.009
34. NO.6 OIL TESTS AT CCRL (MARK II) ERP/ERL 87-22 (CF) [14]:									
OIL01	30.1		0.070		19.7	899		2.09	
OIL02	49.6		0.115		31.6	972		2.26	
OIL03	61.8		0.144		36.2	982		2.28	
OIL04	75.0		0.174		48.0	840		1.95	
OIL05	78.5		0.183		50.1				
OIL06	81.3		0.189		51.3	224		0.52	
OIL07	69.0		0.161		43.9	981		2.28	
OIL08	63.3		0.147		40.1	1215		2.83	
OIL09	53.7		0.125		33.7				
OIL10	49.0		0.114		31.0				
OIL11	52.2		0.121		32.9				
OIL12	49.0		0.114		31.1				
OIL13	55.8		0.130		34.9	122		0.28	
OIL14	59.9		0.139		37.5	205		0.48	
OIL15	55.1		0.128		34.5	768		1.79	
OIL16	51.0		0.119		31.5	1160		2.70	
OIL17	57.4		0.134		35.8				
OIL18	71.7		0.167		44.6				
OIL19	70.3		0.164		43.6				
OIL20	72.7		0.169		45.5	296		0.69	
OIL21	59.5		0.138		37.4				
OIL22	61.9		0.144		38.4				

TABLE 4 SUMMARY OF EMISSION DATA (CONT.)

TEST NO.	NO EMISSION NG/J MEAN	STD.DEV.	NO EMISSION lb/10^6Btu MEAN	STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	STD. DEV.
35. CANMET PITCH TESTS AT CCRL (MARK II), ERP/ERL 87-22 (CF) [14]:									
CP1	87.1		0.203		23.7	1155		2.69	
CP1A	95.2		0.222		26.1	1292		3.01	
CP2	67.6		0.157		18.6				
CP2A	63.1		0.147		26.1				
CP2B	71.7		0.167		19.7				
CP2C	88.6		0.206		24.1				
CP2D	71.7		0.167		19.5	307		0.71	
CP9	59.7		0.139		15.3				
CP9A	81.2		0.189		26.6				
CP9C	74.6		0.174		20.6				
CP9D	68.4		0.159		18.6				
CP9E	67.0		0.156		18.4	258		0.60	
CP7	83.4		0.194		23.2	175		0.41	
36. CANMET PITCH TESTS IN CIRCULATING FBC AT UBC, CONTRACT 24St. 23440-6-9007 [19]:									
1	52.2		0.122		14.2	258		0.60	
2	43.4		0.101		11.8	193		0.45	
3	40.9		0.095		11.1	261		0.61	
4	49.6		0.115		13.5	171		0.40	
37. CANMET PITCH TESTS IN CIRCULATING FBC AT UBC, CONTRACT 52SS. 23440-7-9136 [21]:									
RUN17-B	56.8		0.132		9.6	985		2.29	
RUN17-1	59.9		0.139		10.2	174		0.41	
RUN17-2	72.0		0.168		12.2	166		0.39	
RUN17-4	94.8		0.221		16.1	464		1.08	
RUN17-5	103.4		0.241		17.5	262		0.61	
RUN17-6	100.7		0.234		17.1	272		0.63	

TABLE 4 SUMMARY OF EMISSION DATA (CON'T)

TEST NO.	NO EMISSION NG/J MEAN	STD.DEV.	NO EMISSION lb/10^6Btu MEAN	STD. DEV.	% FUEL N CONVERTED TO NOx	SO2 EMISSION NG/J MEAN	STD. DEV.	SO2 EMISSION lb/10^6Btu MEAN	STD. DEV
38. H-OIL PITCH TESTS IN CIRCULATING FBC AT UBC, CONTRACT 24St.23440-6-9007 [19]:									
1	32.2		0.075		6.3	552		1.28	
2	42.1		0.098		8.2	487		1.13	
3	33.7		0.078		6.6	147		0.34	
39. H-OIL PITCH TESTS IN CIRCULATING FBC AT UBC, CONTRACT 52SS. 23440-7-9136 [21]:									
RUN18-B	81.9		0.190		15.7	1053		2.45	
RUN18-C	64.7		0.150		12.4	290		0.67	
RUN20-B	45.6		0.106		8.7	813		1.89	
RUN20-2	87.5		0.204		16.7	517		1.20	
RUN20-3	112.5		0.262		21.5	232		0.54	
RUN20-4	105.3		0.245		20.1	370		0.86	
40. BITUMEN TESTS AT CCRL (MARK II), ERP/ERL 87-22 (CF) [14]:									
BIT1	40.2		0.093		15.7				
BIT2	63.2		0.147		25.1				
BIT4	45.7		0.106		18.4	656		1.53	

TABLE 5 SUMMARY OF TESTS WITH EXTENSIVE ADDITION OF SORBENT.

FUEL NAME	NO. OF TEST PROGRAMS	NUMBER OF RUNS* BUBBLING PILOT	CIRCULATING PILOT	HEATING PLANT	TOTAL	EXPRESSIONS FOR STANDARDIZED SO2 EMISSION
MINTO COAL	5	37	16	3	56	1.29*exp[-0.581*(Ca/S)] 1.43*exp[-0.628*(Ca/S)]
DEVCO COAL	4	60	0	3	63	1.61*exp[-0.579*(Ca/S)] 1.43*exp[-0.533*(Ca/S)]
EVANS COAL	3	16	0	6	22	1.17*exp[-0.666*(Ca/S)] 1.43*exp[-0.764*(Ca/S)]
BROGAN COAL	1	0	0	3	3	
NOVACO COAL	1	0	0	3	3	
KENTUCKY NO.9 COAL	1	4	0	0	4	
SYNCRUDE COKE	3	16	18	0	34	
NO.6 OIL	1	12	0	0	12	
CANMET PITCH	3	5	10	0	15	
H-OIL PITCH	2	0	9	0	9	

* NUMBER OF RUNS CONDUCTED AT BUBBLING FBC PILOT PLANTS, CIRCULATING FBC PILOT PLANT, THE SUMMERSIDE HEATING PLANT, AND TOTAL RUNS.

TABLE 6 AVERAGE EMISSIONS OF SO2 OBSERVED IN BASE LINE TESTS

NO.	PROGRAM NO.	FUEL NAME	FACILITY	NO. OF RUN	Ca/S	FUEL S (NG/J)	SO2 EMISSION (NG/J)
1	2	MINTO COAL	BUBBLING FBC AT CCRL (MARK I)	12	0.02	3285	4255.3
2	8	DEVCO COAL	BUBBLING FBC AT CCRL (MARK II)	5	0.07	1919	3099.6
3	16	BYRON CREEK COAL	BUBBLING FBC AT CCRL (MARK II)	17	1.34	222	216.7
4	17	LINE CREEK COAL	BUBBLING FBC AT CCRL (MARK I)	24	N/A	109	146.1
5	18	HIGHVALE COAL	BUBBLING FBC AT QUEEN'S UNIV.	7	4.09	130	50.1
6	19	HIGHVALE COAL	BUBBLING FBC AT CCRL (MARK I)	18	5.25	130	82.1
7	20	HIGHVALE COAL	CIRCULATING FBC AT UBC	8	6.97	83	7.2
8	21	WASHED MT KLAPPAN COAL	BUBBLING FBC AT QUEEN'S UNIV.	3	0.22	230	105.7
9	22	MT KLAPPAN COAL	BUBBLING FBC AT QUEEN'S UNIV.	3	0.74	247	158
10	23	MT KLAPPAN COAL	CIRCULATING FBC AT UBC	6	1.25	176	138.7
11	24	ONAKAWANA LIGNITE	BUBBLING FBC AT CCRL (MARK I)	7	1.82	644	882.1
12	25	ONAKAWANA LIGNITE	BUBBLING FBC AT CCRL (MARK II)	6	1.82	644	566.8
13	26	POPLAR RIVER LIGNITE	CIRCULATING FBC AT UBC	4	2.32	375	10
14	27	WASHERY REJECT	BUBBLING FBC AT CCRL (MARK II)	2	0.07	2158	3616.5
15	29	SYNCRUDE COKE	BUBBLING FBC AT CCRL (MARK II)	3	0.05	2283	2755.3
16	30	SYNCRUDE COKE	CIRCULATING FBC IN FINLAND	3	0.05	2311	4082.7
17	31	SUNCOR COKE	BUBBLING FBC AT CCRL (MARK I)	9	0.01	1701	2258.7
18	32	SASKATCHEWAN COKE	BUBBLING FBC AT QUEEN'S UNIV.	11	0.06	833	1116.1
19	33	COAL/WATER SLURRY	BUBBLING FBC AT QUEEN'S UNIV.	14	0.04	1006	724.5
20	34	NO.6 OIL	BUBBLING FBC AT CCRL (MARK II)	8	N/A	583	977.1
21	35	CANMET PITCH	BUBBLING FBC AT CCRL (MARK II)	2	0.05	560	1223.5
22	37	CANMET PITCH	CIRCULATING FBC AT UBC	1	0.05	700	985
23	39	H-OIL PITCH	CIRCULATING FBC AT UBC	2	0	561	933

TABLE 7 AVERAGE EMISSIONS OF NOx OBSERVED IN EACH TEST PROGRAM

PROGRAM NO.	FUEL NAME	FACILITY	NO. OF RUN	FUEL N (NG/J)	NOx EMISSION (NG/J) MAX.	MIN.	AVG.
1	MINTO COAL	BUBBLING FBC AT QUEEN'S UNIV.	19	280	148.4	64.2	110.8
2	MINTO COAL	BUBBLING FBC AT CCRL (MARK I)	18	277	86.5	3.0	38.0
3	MINTO COAL	SUMMERSIDE HEATING PLANT	3	340	245.4	113.1	178.8
4	MINTO COAL	CIRCULATING FBC AT UBC	9	251	54.5	41.8	49.0
5	MINTO COAL	CIRCULATING FBC AT UBC	7	288	109.3	47.4	82.8
6	DEVCO COAL	BUBBLING FBC AT QUEEN'S UNIV.	4	437	199.9	149.6	179.3
7	DEVCO COAL	BUBBLING FBC AT QUEEN'S UNIV.	8	434	275.0	116.5	158.7
8	DEVCO COAL	BUBBLING FBC AT CCRL (MARK II)	36	517	202.9	87.9	136.4
9	DEVCO COAL	SUMMERSIDE HEATING PLANT	3	409	163.2	70.3	127.0
10	EVANS COAL	BUBBLING FBC AT QUEEN'S UNIV.	16	414	133.6	33.7	84.5
11	EVANS COAL	SUMMERSIDE HEATING PLANT	3	456	225.2	168.9	199.4
12	EVANS COAL	SUMMERSIDE HEATING PLANT	3	456	300.9	257.9	275.1
13	BROGAN COAL	SUMMERSIDE HEATING PLANT	3	444	186.3	146.9	160.3
14	NOVACO COAL	SUMMERSIDE HEATING PLANT	3	515	279.5	199.9	228.7
15	KENTUCKY NO.9 COAL	BUBBLING FBC AT QUEEN'S UNIV.	4	502	142.0	89.4	122.8
16	BYRON CREEK COAL	BUBBLING FBC AT CCRL (MARK II)	17	407	112.6	6.4	80.3
17	LINE CREEK COAL	BUBBLING FBC AT CCRL (MARK I)	24	327	160.4	19.8	89.1
18	HIGHVALE COAL	BUBBLING FBC AT QUEEN'S UNIV.	7	303	197.4	43.3	109.6
19	HIGHVALE COAL	BUBBLING FBC AT CCRL (MARK I)	18	303	98.4	31.0	64.0
20	HIGHVALE COAL	CIRCULATING FBC AT UBC	8	333	82.2	19.7	55.3

TABLE 7 AVERAGE EMISSIONS OF NOx OBSERVED IN EACH TEST PROGRAM (CONT.)

PROGRAM NO.	FUEL NAME	FACILITY	NO. OF RUN	FUEL N (NG/J)	NOx EMISSION (NG/J) MAX.	MIN.	AVG.
21	WASHED MT KLAPPAN COAL	BUBBLING FBC AT QUEEN'S UNIV.	3	361	149.4	53.4	107.7
22	MT KLAPPAN COAL	BUBBLING FBC AT QUEEN'S UNIV.	3	370	63.1	29.3	51.3
23	MT KLAPPAN COAL	CIRCULATING FBC AT UBC	6	317	86.9	24.1	42.9
24	ONAKAWANA LIGNITE	BUBBLING FBC AT CCRL (MARK I)	8	396	198.9	30.2	65.0
25	ONAKAWANA LIGNITE	BUBBLING FBC AT CCRL (MARK II)	9	396	95.5	52.1	73.8
26	POPLAR RIVER LIGNITE	CIRCULATING FBC AT UBC	4	292	53.6	42.4	49.9
27	WASHERY REJECT FROM DEVCO COAL	BUBBLING FBC AT CCRL (MARK II)	12	539	188.4	101.7	137.0
28	SYNCRUDE COKE	BUBBLING FBC AT QUEEN'S UNIV.	9	636	322.4	78.1	196.0
29	SYNCRUDE COKE	BUBBLING FBC AT CCRL (MARK II)	7	623	298.6	69.3	167.4
30	SYNCRUDE COKE	CIRCULATING FBC PILOT PLAN IN KARHULA FINLAND	18	490	220.0	22.8	83.2
31	SUNCOR COKE	BUBBLING FBC AT CCRL (MARK I)	10	418	214.5	6.3	53.2
32	SASKATCHEWAN COKE	BUBBLING FBC AT QUEEN'S UNIV.	14	345	171.7	50.1	105.4
33	COAL/WATER SLURRY	BUBBLING FBC AT QUEEN'S UNIV.	17	422	212.7	23.6	144.5
34	NO.6 OIL	BUBBLING FBC AT CCRL (MARK II)	22	70	81.3	30.1	60.4
35	CANMET PITCH	BUBBLING FBC AT CCRL (MARK II)	13	169	95.2	59.8	75.4
36	CANMET PITCH	CIRCULATING FBC AT UBC	4	169	52.2	40.9	46.5
37	CANMET PITCH	CIRCULATING FBC AT UBC	6	275	103.4	56.8	81.3
38	H-OIL PITCH	CIRCULATING FBC AT UBC	3	244	42.1	32.2	36.0
39	H-OIL PITCH	CIRCULATING FBC AT UBC	6	244	112.5	45.6	82.9
40	BITUMEN	BUBBLING FBC AT CCRL (MARK II)	3	123	63.3	40.2	49.7

TABLE 8 EFFECT OF OPERATING PARAMETERS ON NOx EMISSION

FACILITY	INCREASE OF NOx WITH EXCESS O2	INCREASE OF NOx WITH BED TEMPERATURE	DECREASE OF NOx WITH CO	EFFECT OF FUEL FIRING RATE ON NOx	INCREASE OF NOx WITH Ca/S
MARK I BUBBLING FBC PILOT PLANT	NONE	CONSISTANT* STRONG	YES**	NONE	YES
MARK II BUBBLING FBC PILOT PLANT	NONE	YES	CONSISTANT	NONE	NONE
QUEEN'S UNIV. BUBBLING FBC PILOT PLANT	CONSISTANT STRONG	NONE	CONSISTANT	NONE	NONE
UBC CIRCULATING FBC PILOT PLANT	CONSISTANT	CONSISTANT	INCONCLUSIVE	NONE	CONSISTANT STRONG
FINLAND CIRCULATING FBC PILOT PLANT	NONE	YES	YES	NONE	NONE
SUMMERSIDE BUBBLING FBC HEATING PLANT	SLIGHTLY REVERSE	NONE	CONSISTANT STRONG	NONE	NONE

* THE TREND IS CONSISTANT FOR THE TESTS CONDUCTED AT THIS PLANT WITH DIFFERENT FUELS.

** THE TREND IS OBSERVED. HOWEVER, THE DATA ARE AVAILABLE ONLY FOR TESTS WITH ONE OR TWO FUELS.

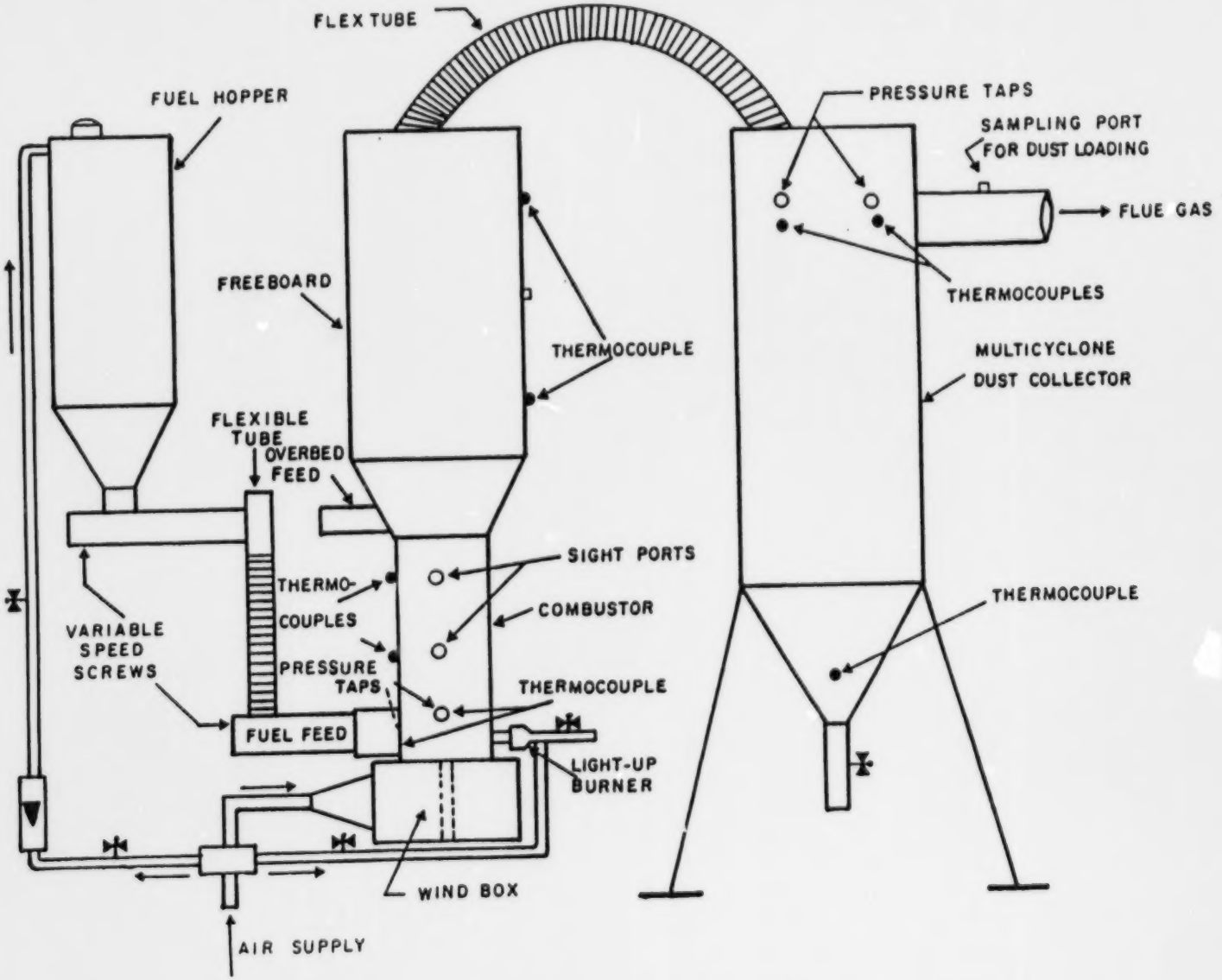

Fig. 1 Schematic overview of the fluidized bed combustor mark I

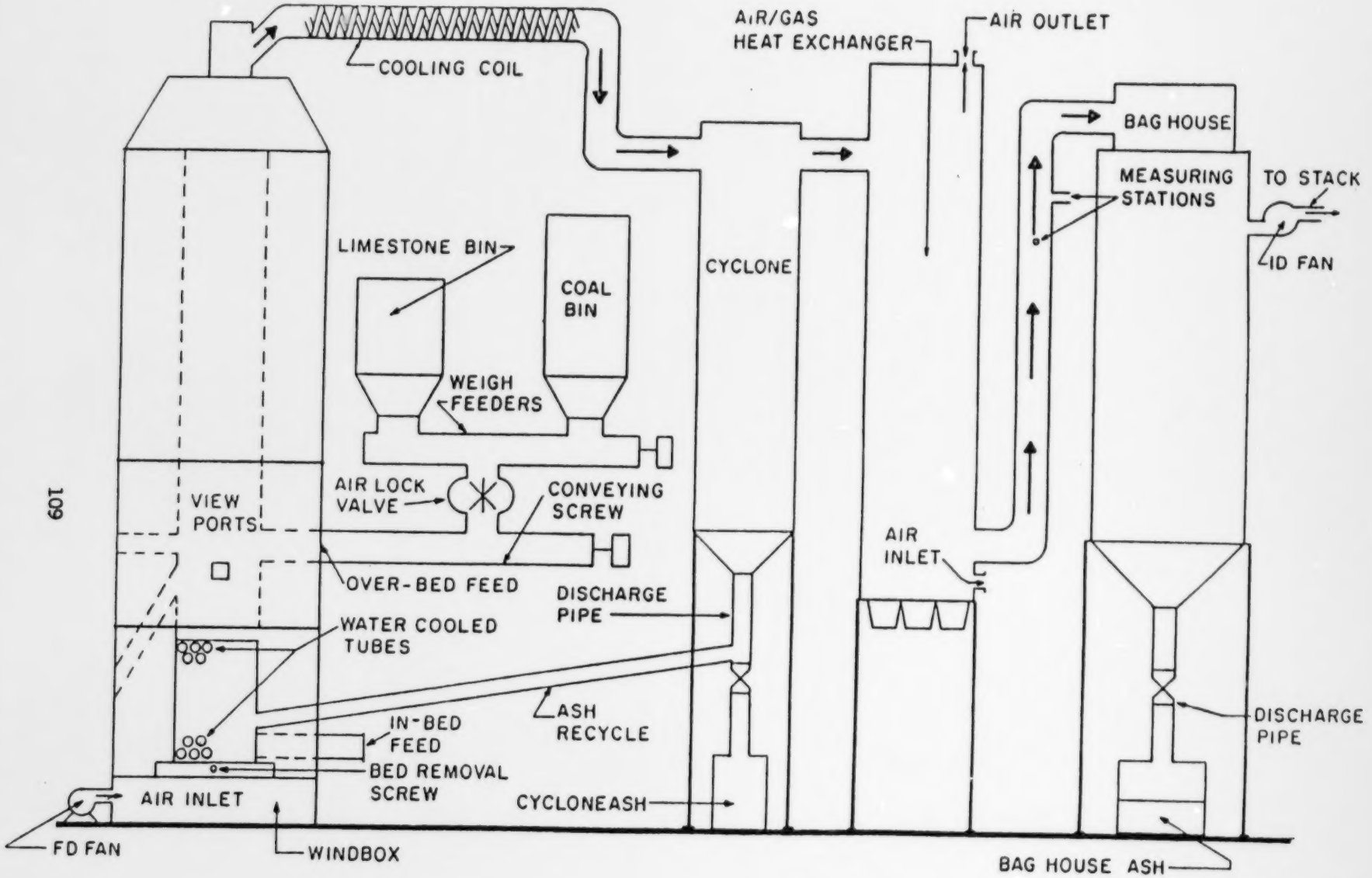

Fig. 2 Schematic diagram of the fluidized bed combustor mark II

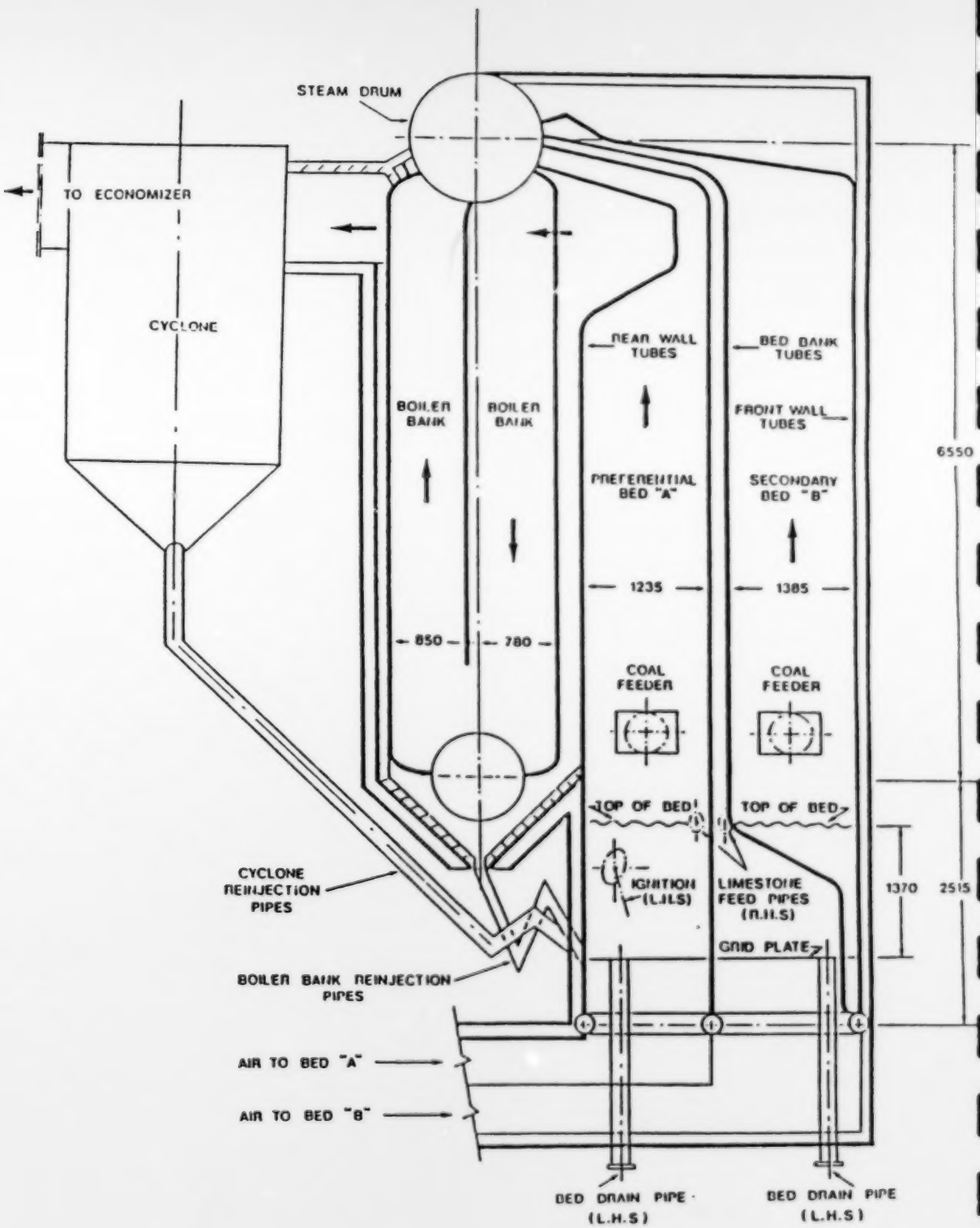

Fig. 3 Section view of bubbling fluidized bed boiler at Summerside, Prince Edward Island

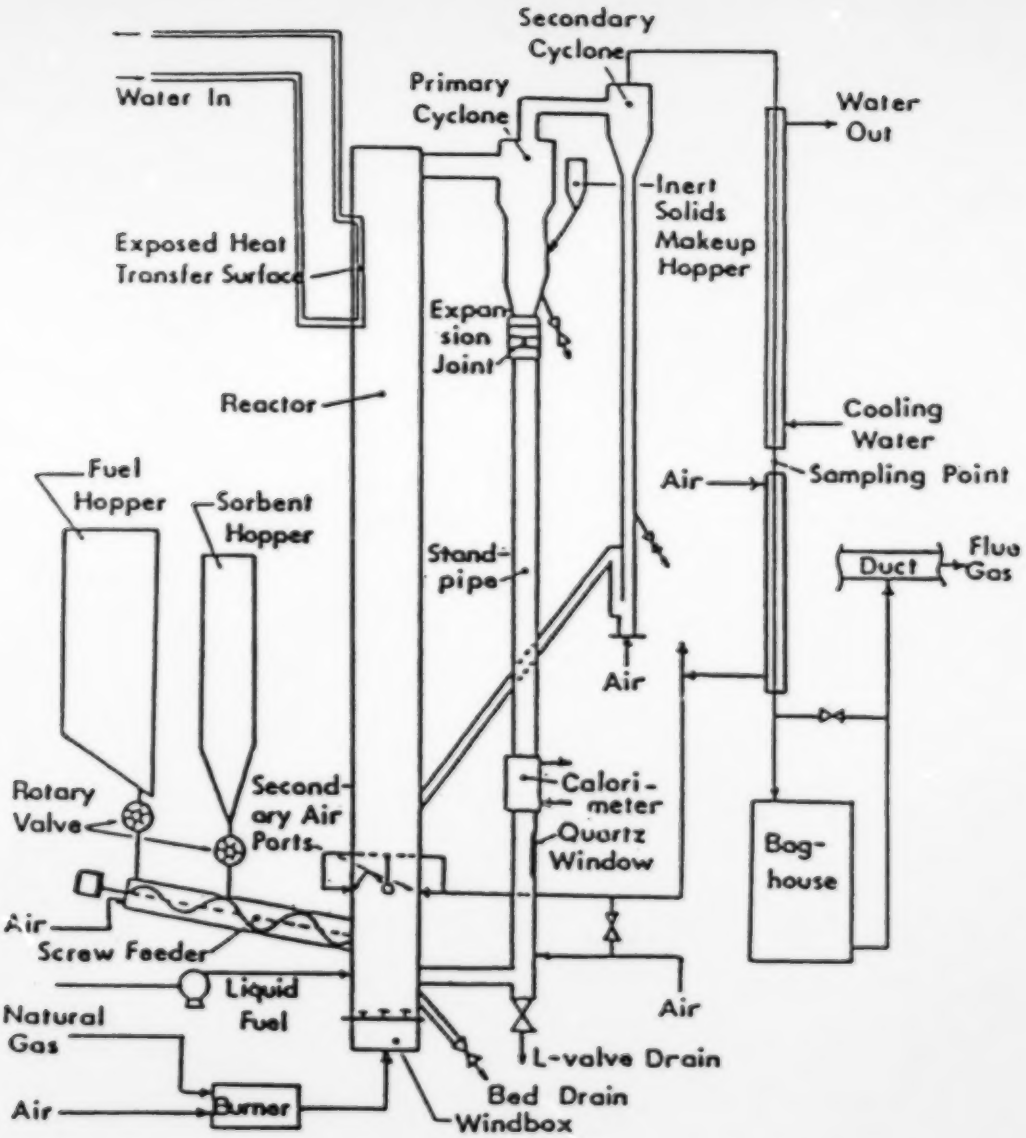

Fig. 4 Schematic diagram of the circulating fluidized bed combustion facility at UBC

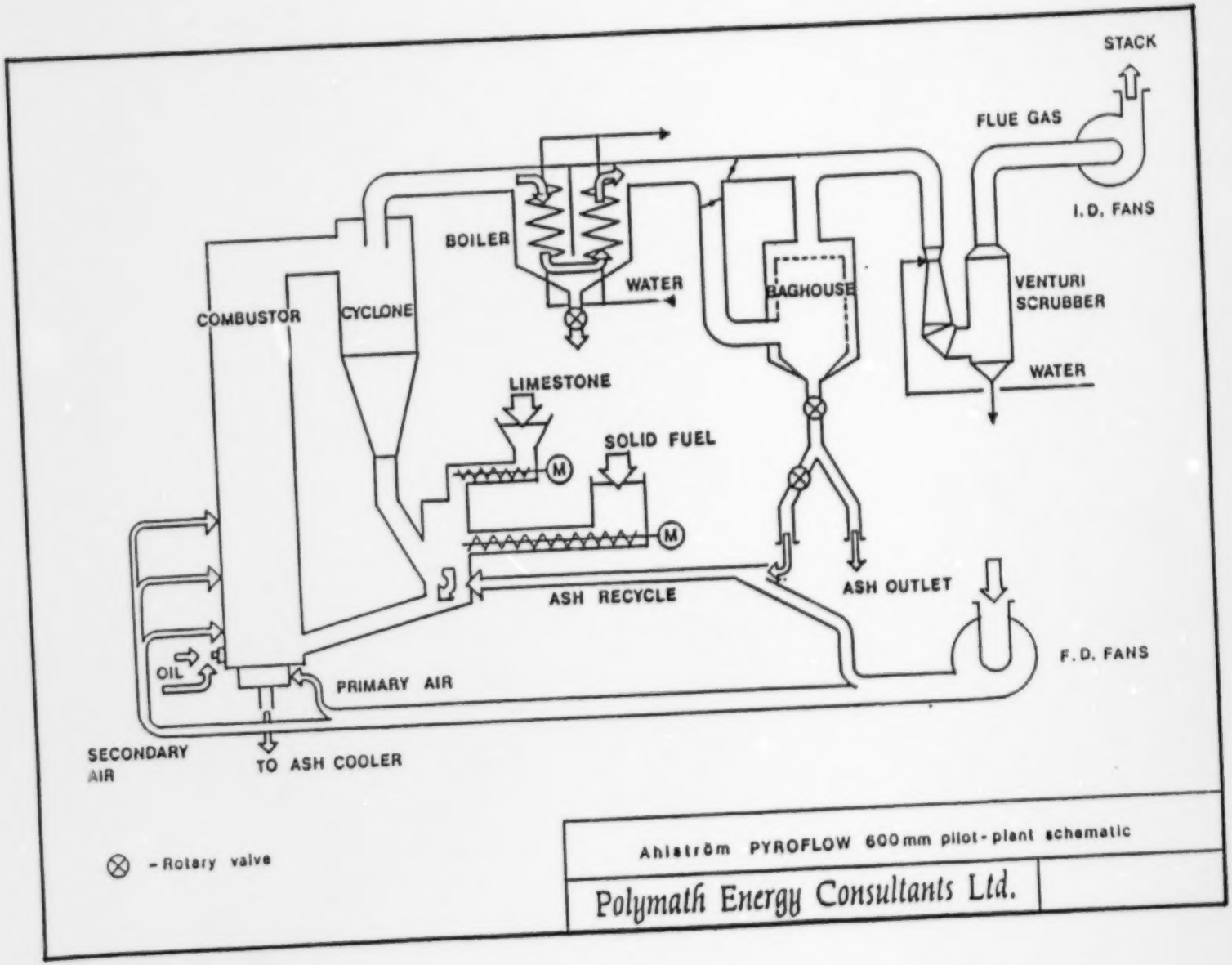

Fig. 5 Schematic of circulating fluidized bed combustion facility at Karhula, Finland

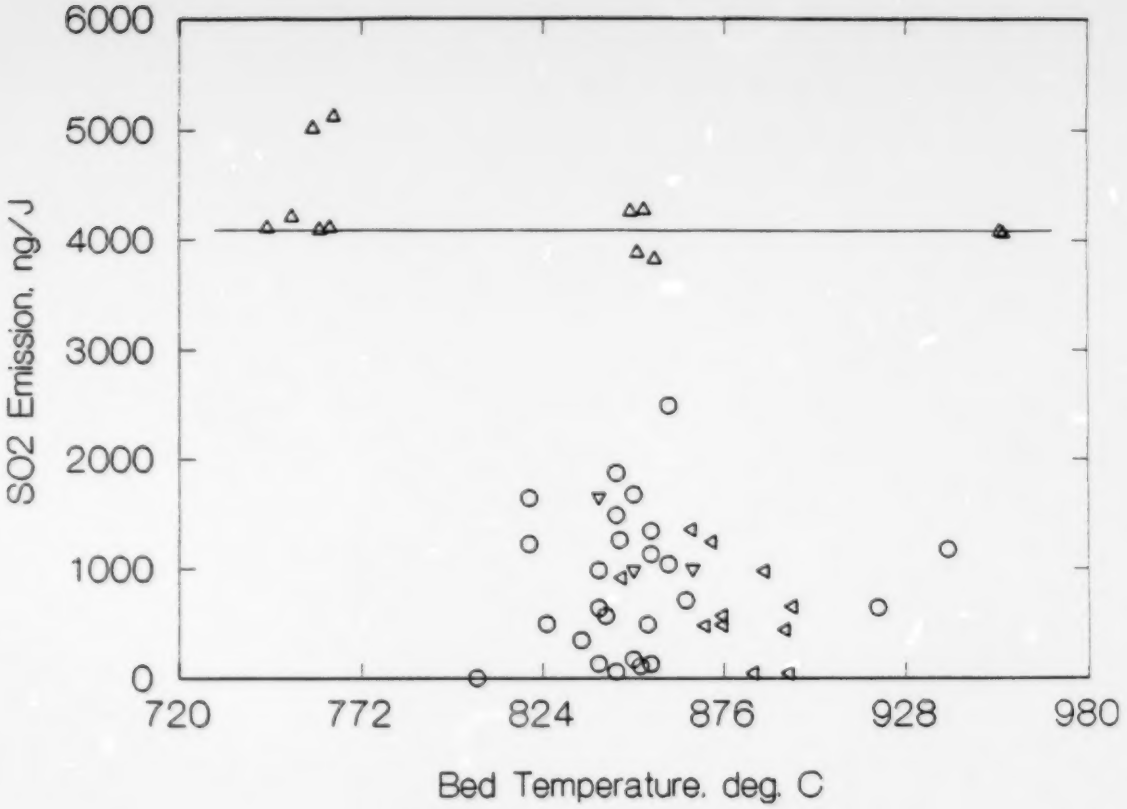

Fig. 6 Effect of bed temperature on SO_2 emission of Minto coal.

Legend: △ Mark I bubbling FBC, base line tests
○ Queen's Univ. bubbling FBC, Ca/S = 1.25-4.47
▽ Summerside heating plant, Ca/S = 1.62-2.39
◁ UBC circulating FBC, Ca/S = 1.36-3

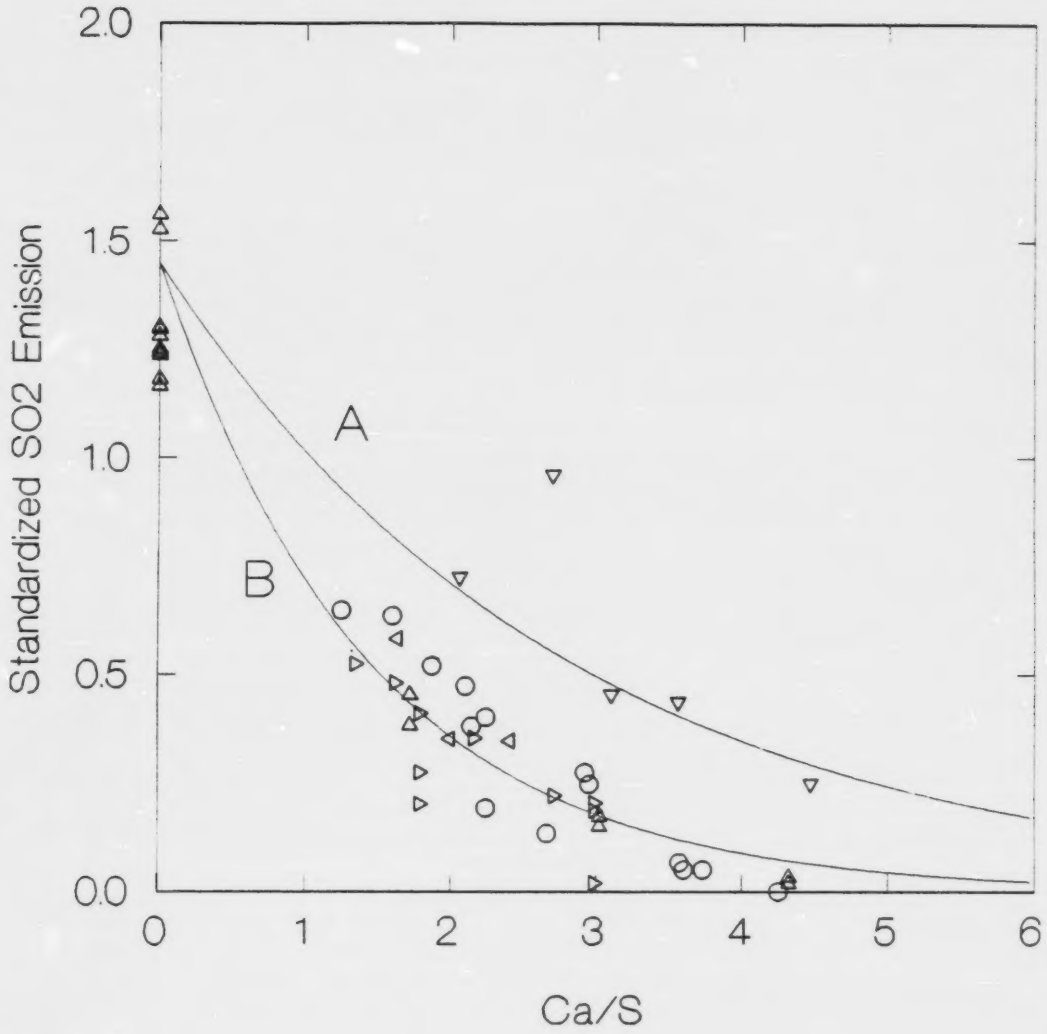

Fig. 7 Effect of Ca/S molar ratio on standardized SO_2 emission of Minto coal.

Facility and limestone size:

- ○ Queen's Univ. bubbling FBC, 0.49-1.1 mm
- ▽ Queen's Univ. bubbling FBC, 1.72-1.98 mm
- △ Mark I bubbling FBC, 1.1 mm
- ◁ Summerside heating plant, 0.85-2.36 mm
- ▷ UBC circulating FBC, 0.21-0.45 mm

Model:

- A Eq. 4.7.14
- B Eq. 4.7.15

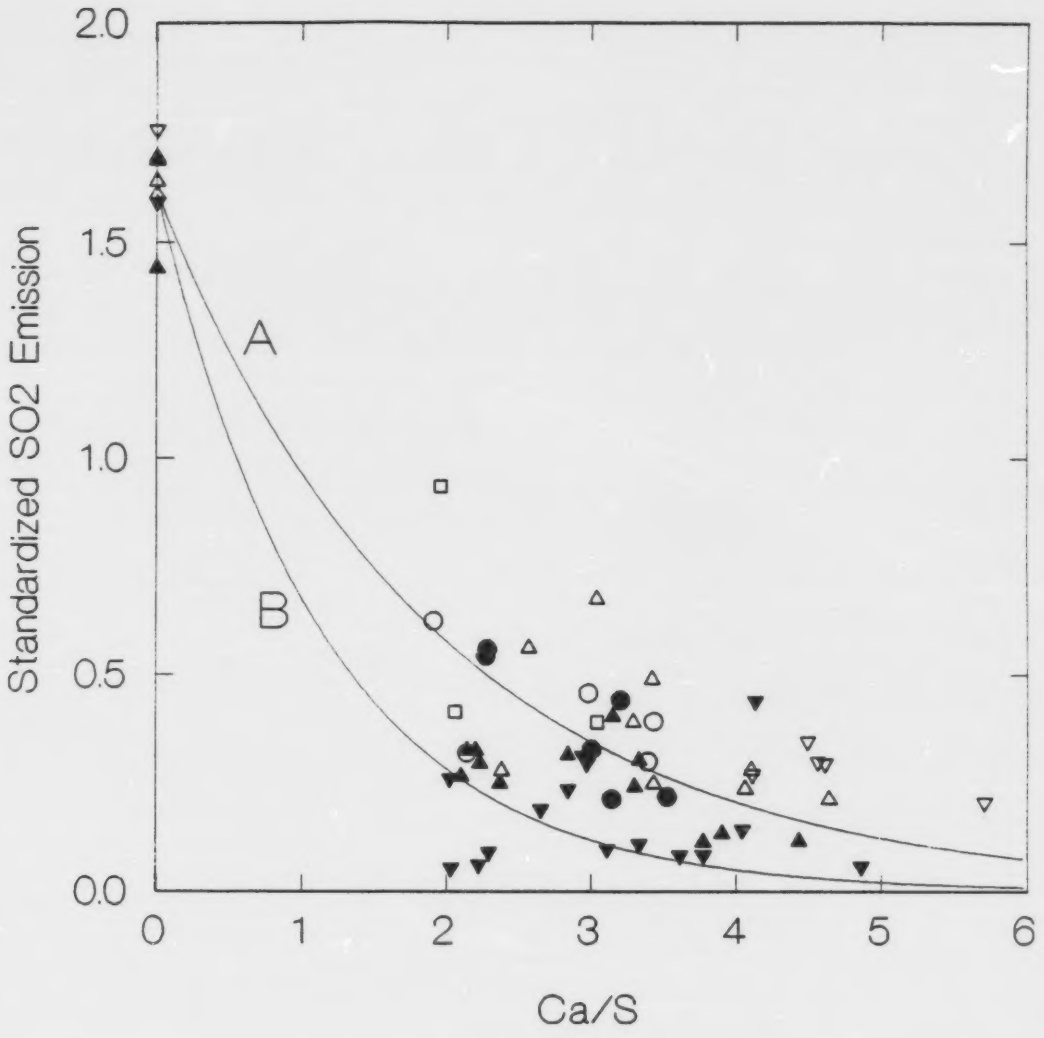

Fig. 8 Effect of Ca/S molar ratio on standardized SO_2 emission of Devco coal.

Facility and limestone size:

○ ● Queen's Univ. bubbling FBC, 1.1-1.72 mm
△ ▲ Mark II bubbling FBC, 0.84-6 mm
▽ ▼ Mark II bubbling FBC, 0-6.3 mm
□ Summerside heating plant, 0.85-2.36 mm

Recycle:

●▲▼ with recycle
○△▽ without recycle

Model:

A Eq. 4.7.17
B Eq. 4.7.16

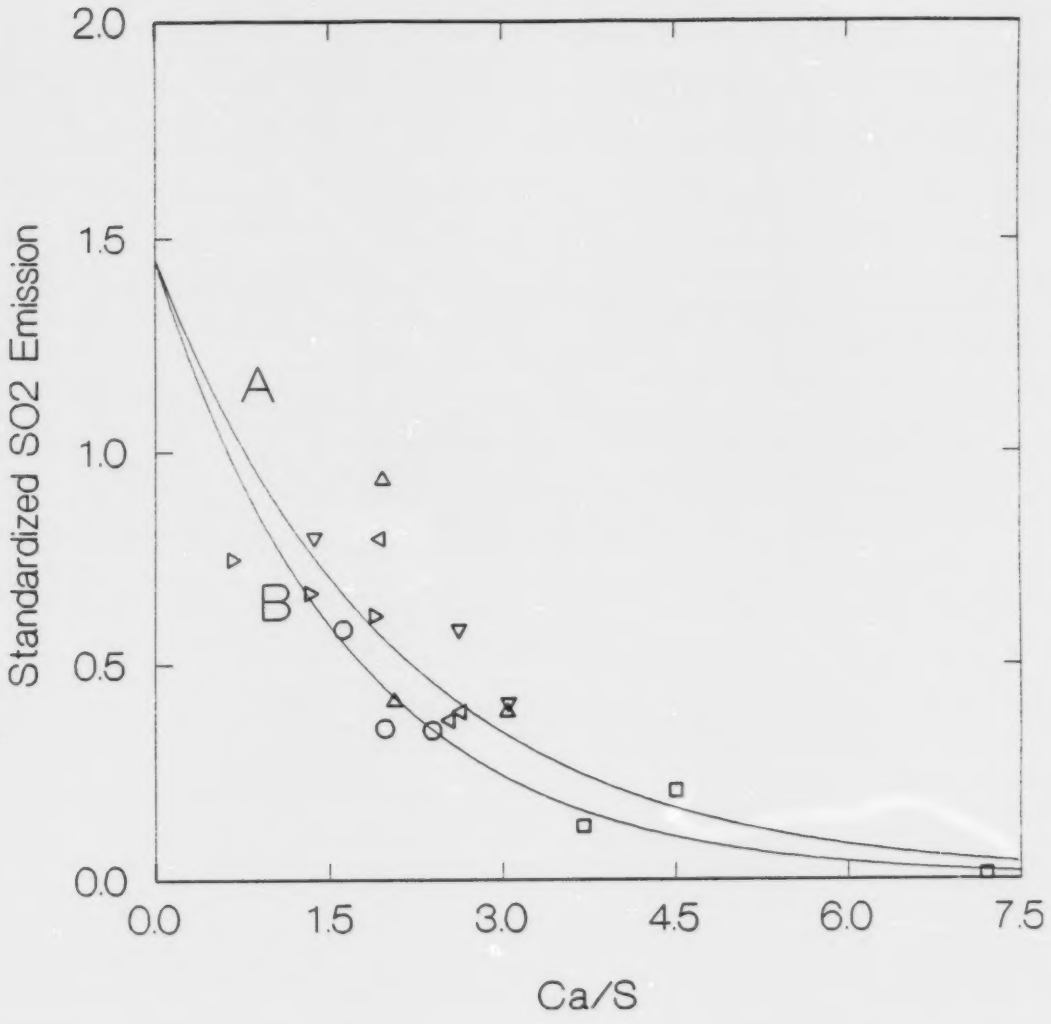

Fig. 9 Effect of Ca/S molar ratio on SO_2 emission observed at Summerside heating plant.

Coal:	▽	Evans, CANMET tests	□	Evans, US EPA tests
	○	Minto	△	Devco
	◁	Brogan	▷	Novaco
Model:	A	Eq. 4.7.19	B	Eq. 4.7.18

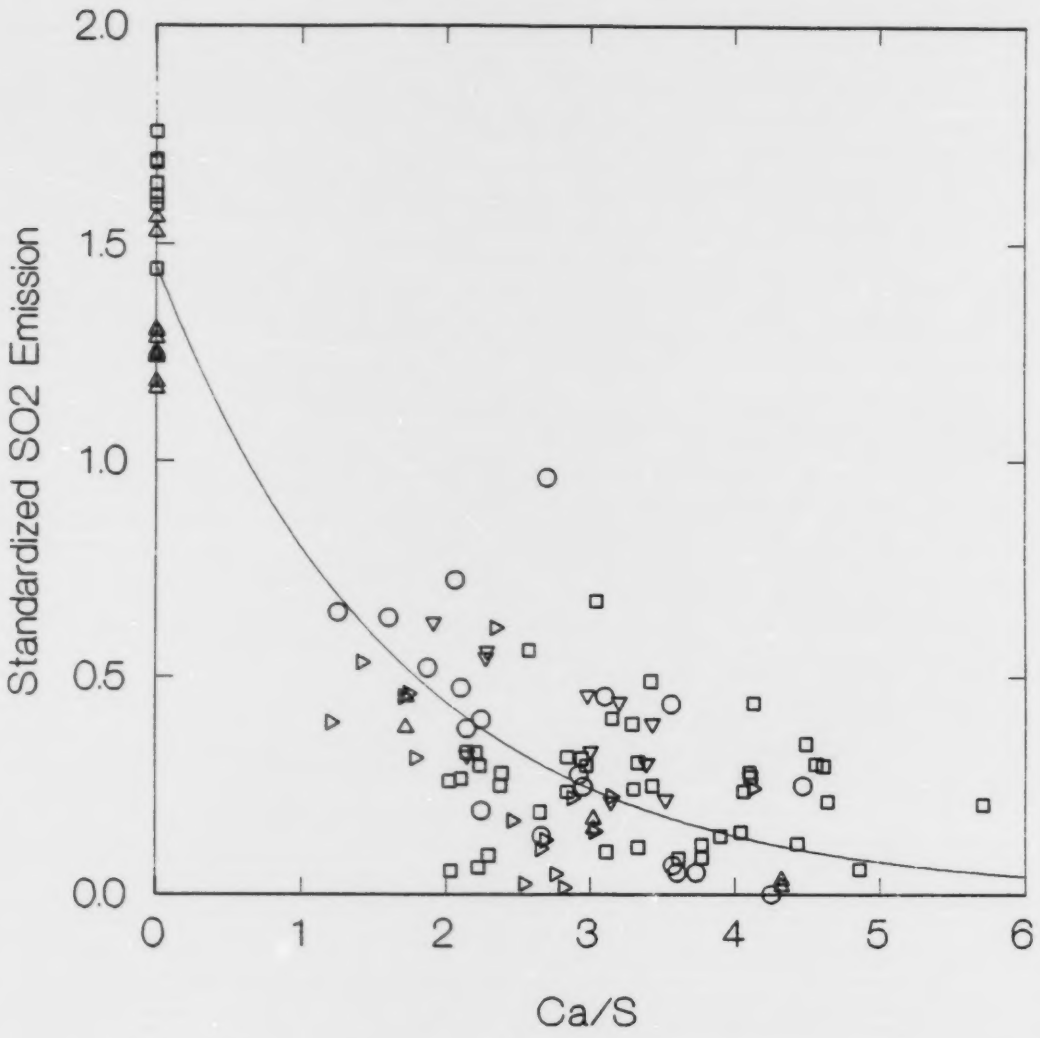

Fig. 10 Effect of Ca/S molar ratio on standardized SO_2 emission observed in bubbling FBC pilot-plant tests.

Coal and facility:
- ○ Minto, Queen's Univ.
- △ Minto, Mark I
- ▽ Devco, Queen's Univ.
- □ Devco, Mark II
- ▷ Evans, Queen's Univ.

Model: Eq. 4.7.18

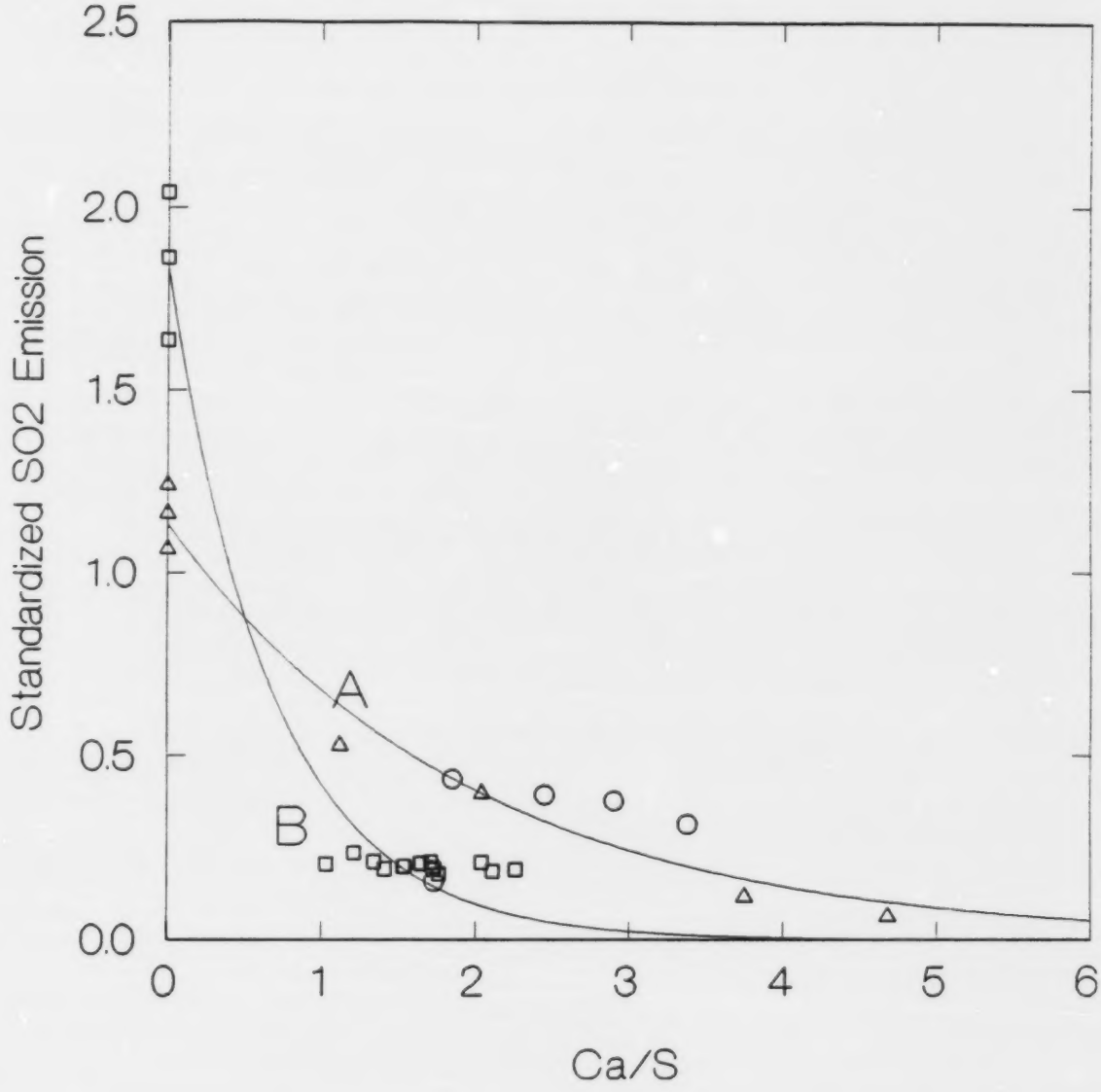

Fig. 11 Effect of Ca/S molar ratio on standardized SO_2 emission of Syncrude coke. Results for bed temperature above 1050 deg. C are excluded.

Facility:	O	Queen's Univ. bubbling FBC
	Δ	Mark II bubbling FBC
	□	circulating FBC in Finland
Model:	A	bubbling FBC tests
	B	circulating FBC tests

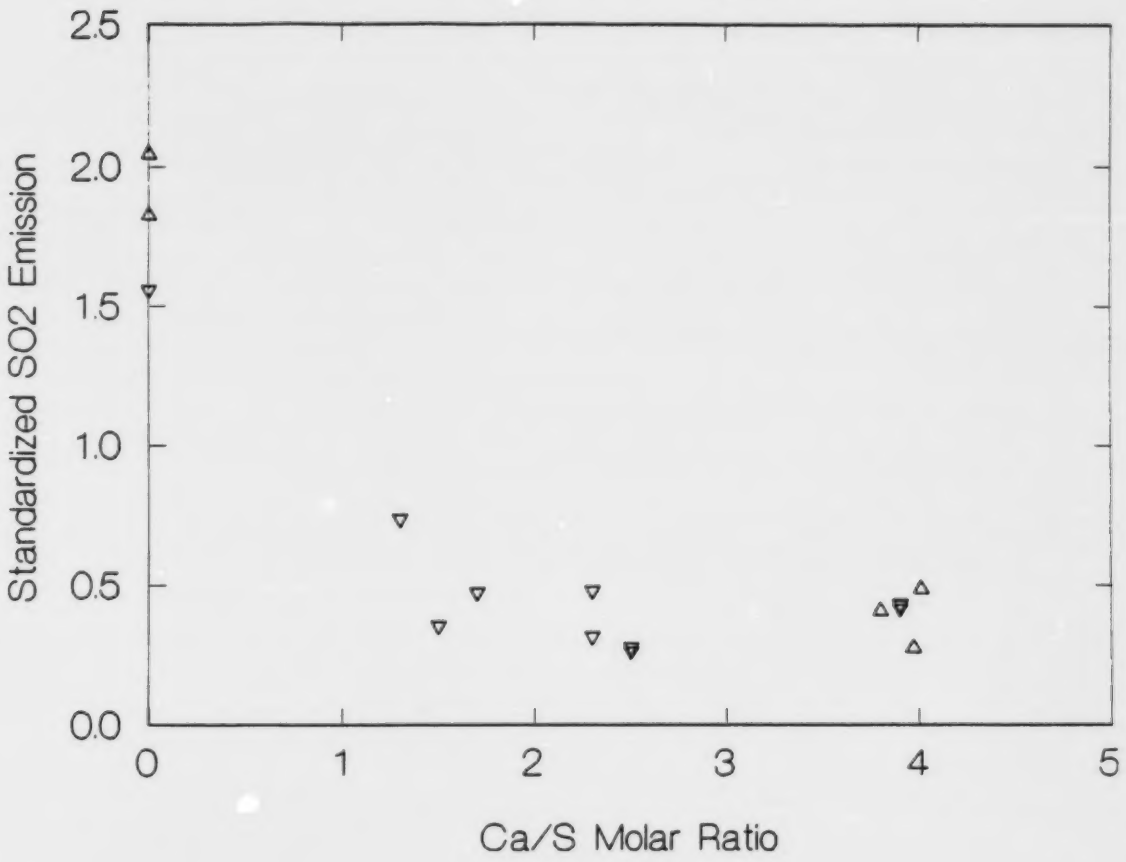

Fig. 12 Comparison of standardized SO_2 emission observed in circulating FBC and bubbling FBC tests with CANMET pitch.

Legend: △ Mark II bubbling FBC
▽ UBC circulating FBC

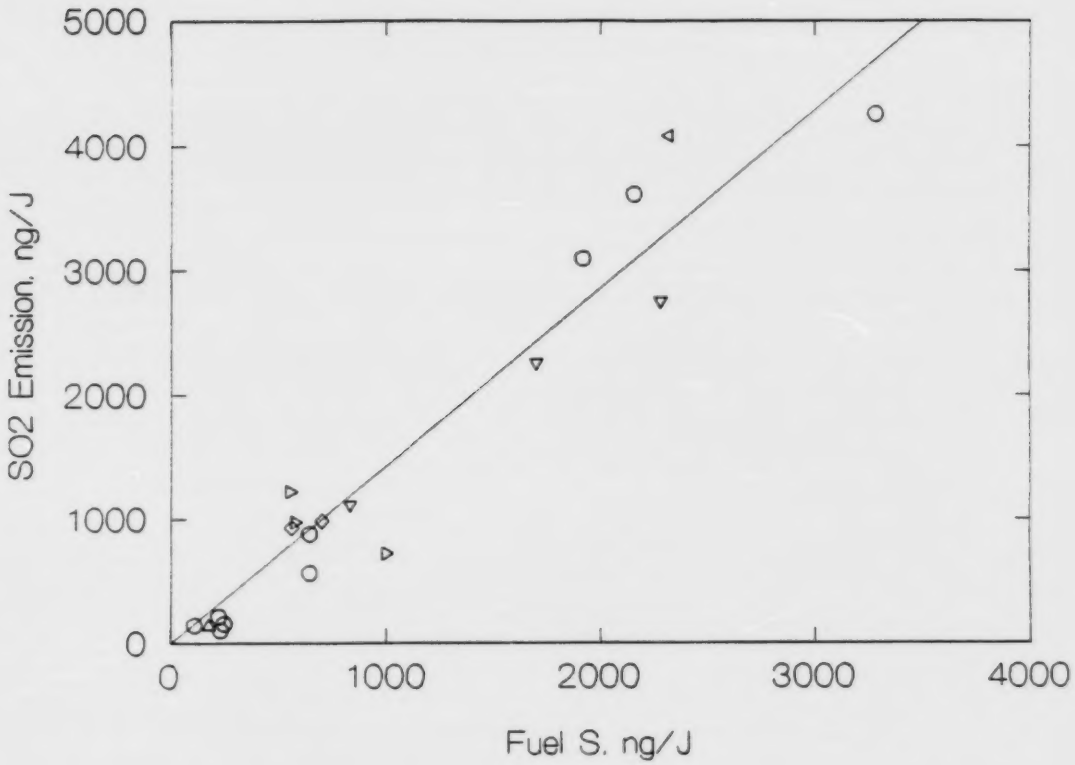

Fig. 13 Effect of fuel S on SO_2 emission.

Legend:
- ○ coal, bubbling FBC
- △ coal, circulating FBC
- ▽ petroleum coke, bubbling FBC
- ◁ petroleum coke, circulating FBC
- ▷ liquid fuel, bubbling FBC
- ◇ liquid fuel, circulating FBC

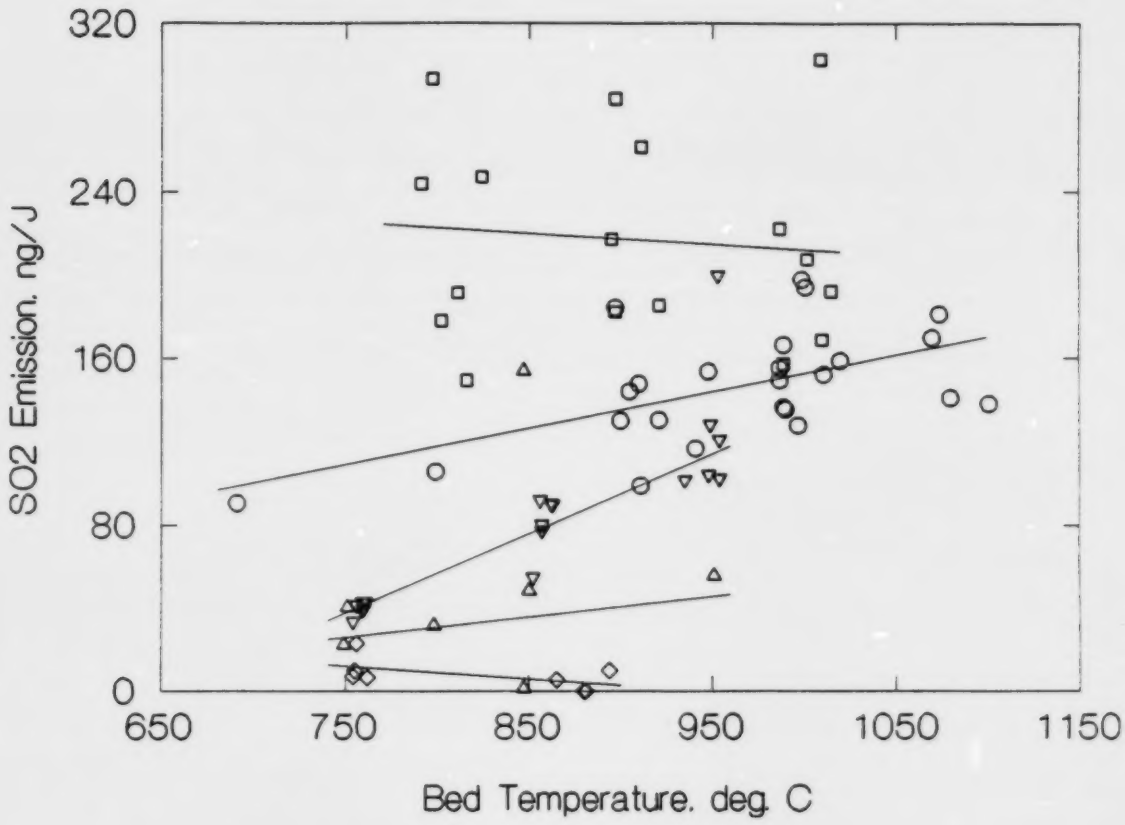

Fig. 14 Effect of bed temperature on SO_2 emission observed in base line tests of three coals.

Legend:
- □ Byron Creek coal, Mark II bubbling FBC
- ○ Line Creek coal, Mark I bubbling FBC
- △ Highvale coal, Queen's Univ. bubbling FBC
- ▽ Highvale coal, Mark I bubbling FBC
- ◇ Highvale coal, UBC circulating FBC

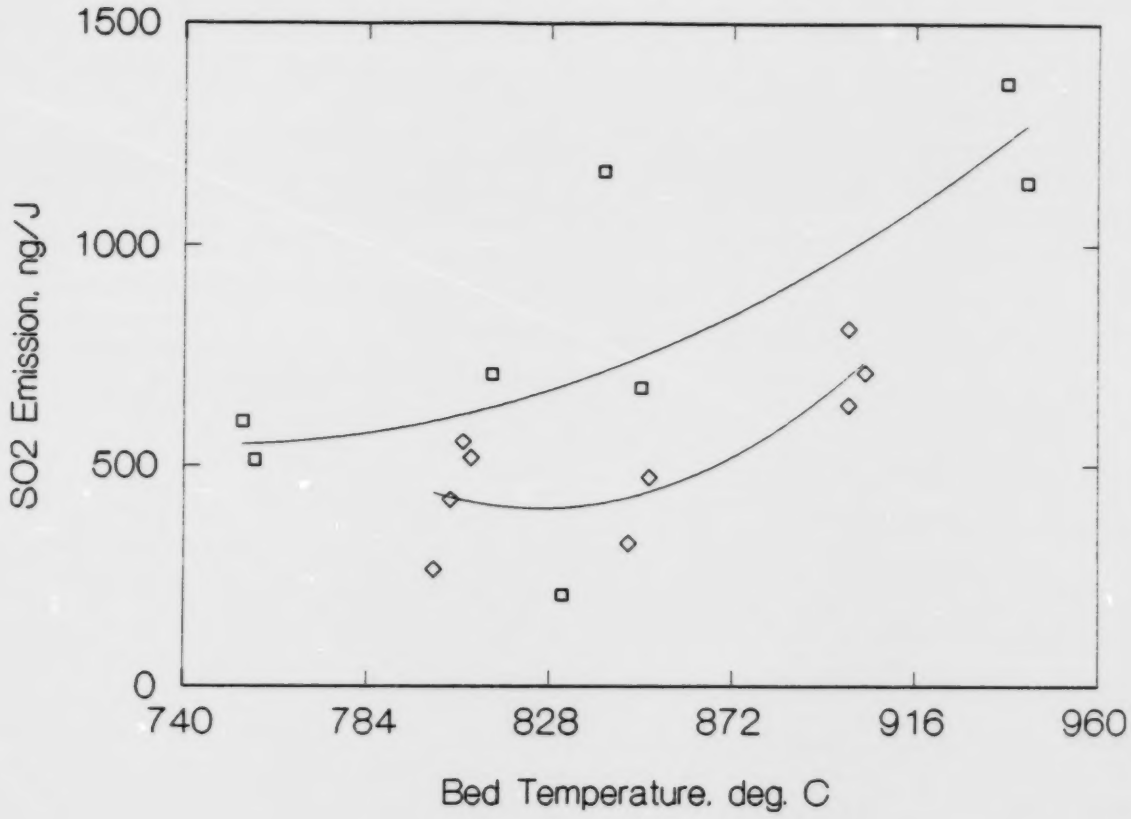

Fig. 15 Effect of bed temperature on SO_2 emission of Onakawana lignite.

Facility: □ **Mark I bubbling FBC**
◇ **Mark II bubbling FBC**

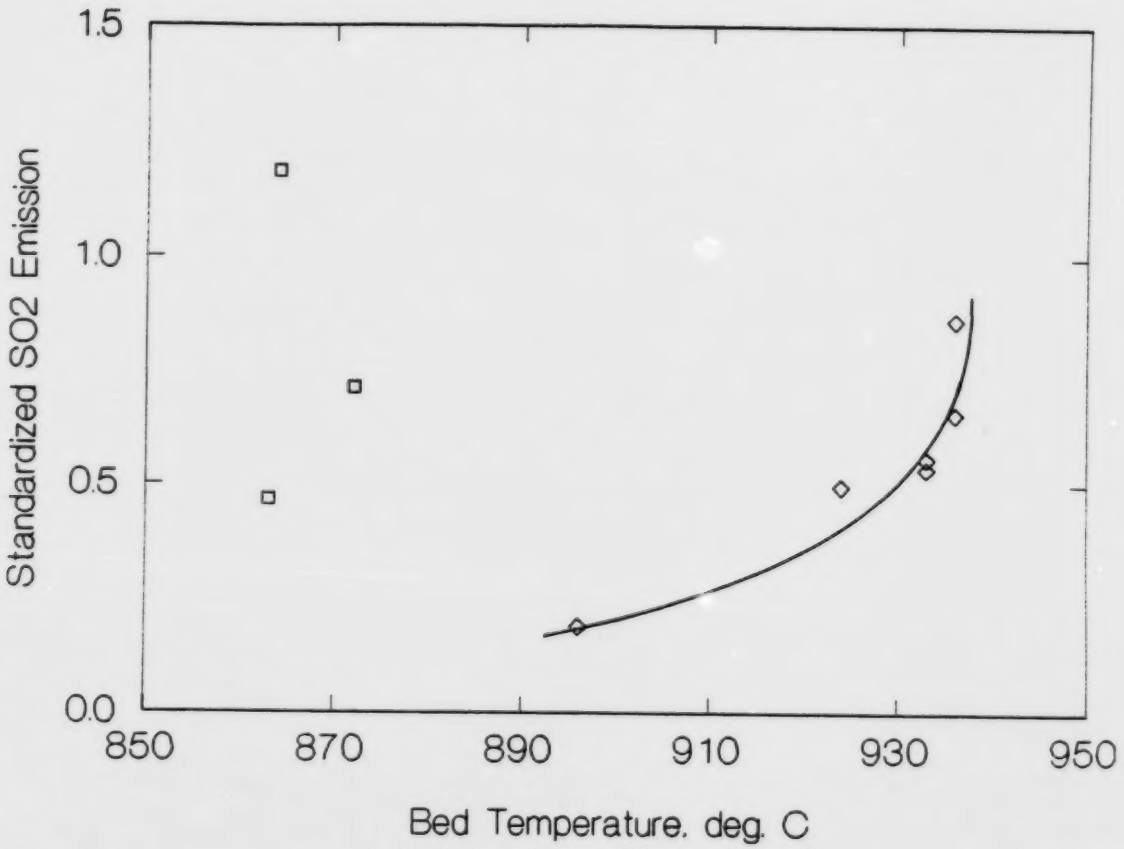

Fig. 16 Effect of bed temperature on standardized SO_2 emission of Mt Klappan anthracite observed in base line tests.

Facility: ◇ **Queen's Univ. bubbling FBC**
□ **UBC circulating FBC**

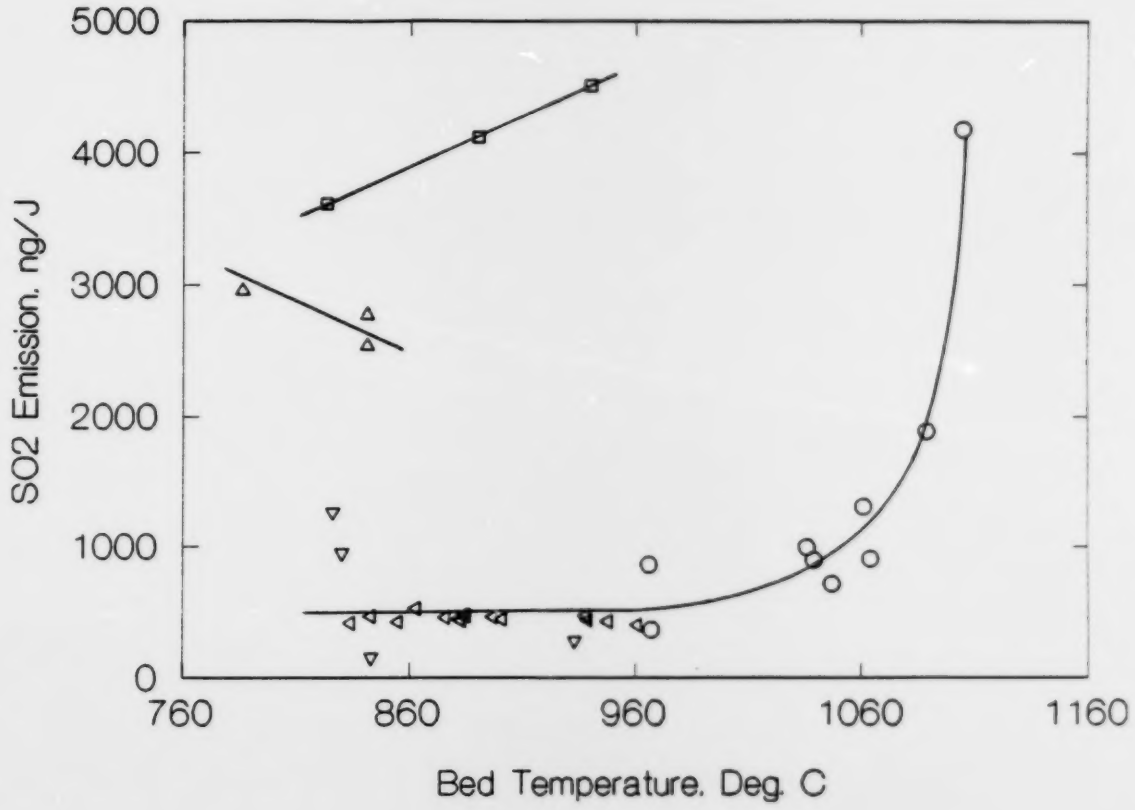

Fig. 17 Effect of bed temperature on SO_2 emission of Syncrude coke.

Legend:
- ○ Queen's Univ. bubbling FBC, Ca/S = 1.73-3.38
- ▽ Mark II bubbling FBC, Ca/S = 1.12-4.68
- ◁ circulating FBC in Finland, Ca/S = 1.03-2.26
- △ Mark II bubbling FBC, baseline tests
- □ circulating FBC in Finland, base line tests

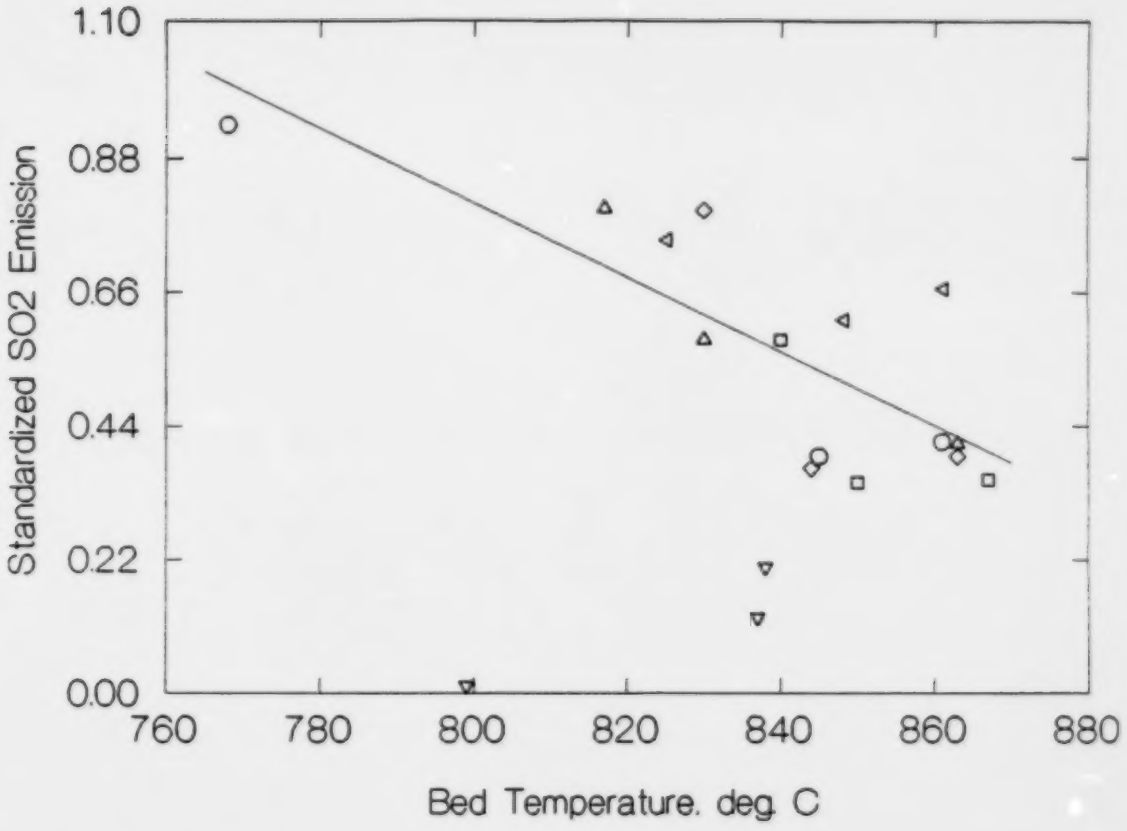

Fig. 18 Effect of bed temperature on standardized SO_2 emission observed at Summerside heating plant.

Coal: △ **Evans, CANMET tests** ▽ **Evans, US EPA tests**
□ **Minto** ○ **Devco**
◁ **Novaco** ◇ **Brogan**

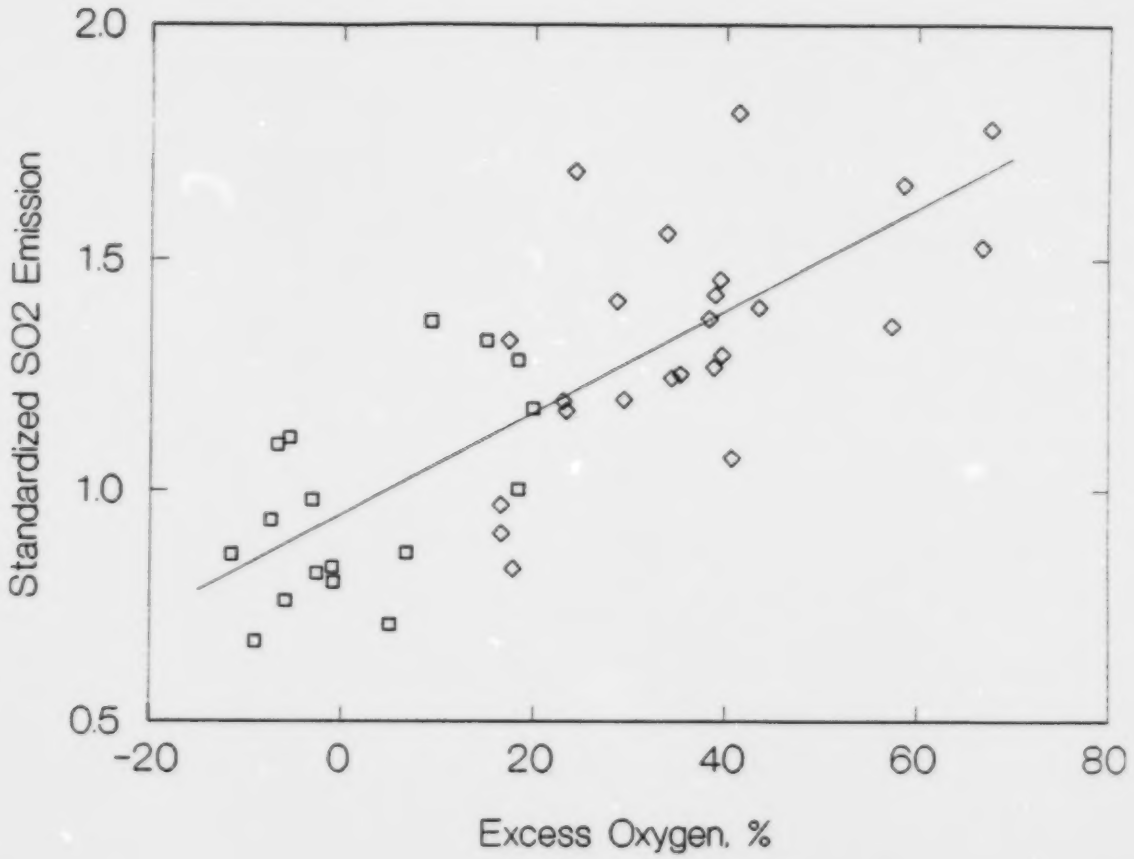

Fig. 19 Effect of excess O_2 on standardized SO_2 emission.

Legend: □ Byron Creek coal, Mark II bubbling FBC
◇ Line Creek coal, Mark I bubbling FBC

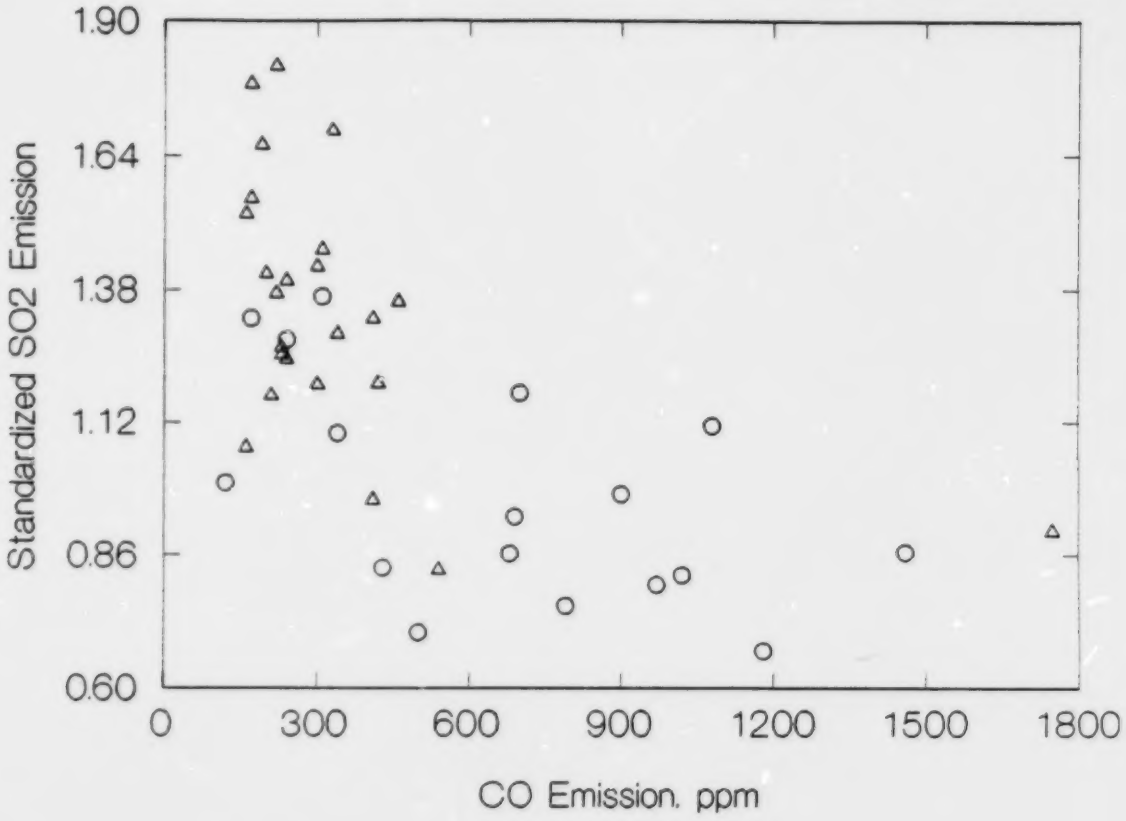

Fig. 20 Effect of CO emission level on standardized SO_2 emission.

Legend: ○ Byron Creek coal, Mark II bubbling FBC
△ Line Creek coal, Mark I bubbling FBC

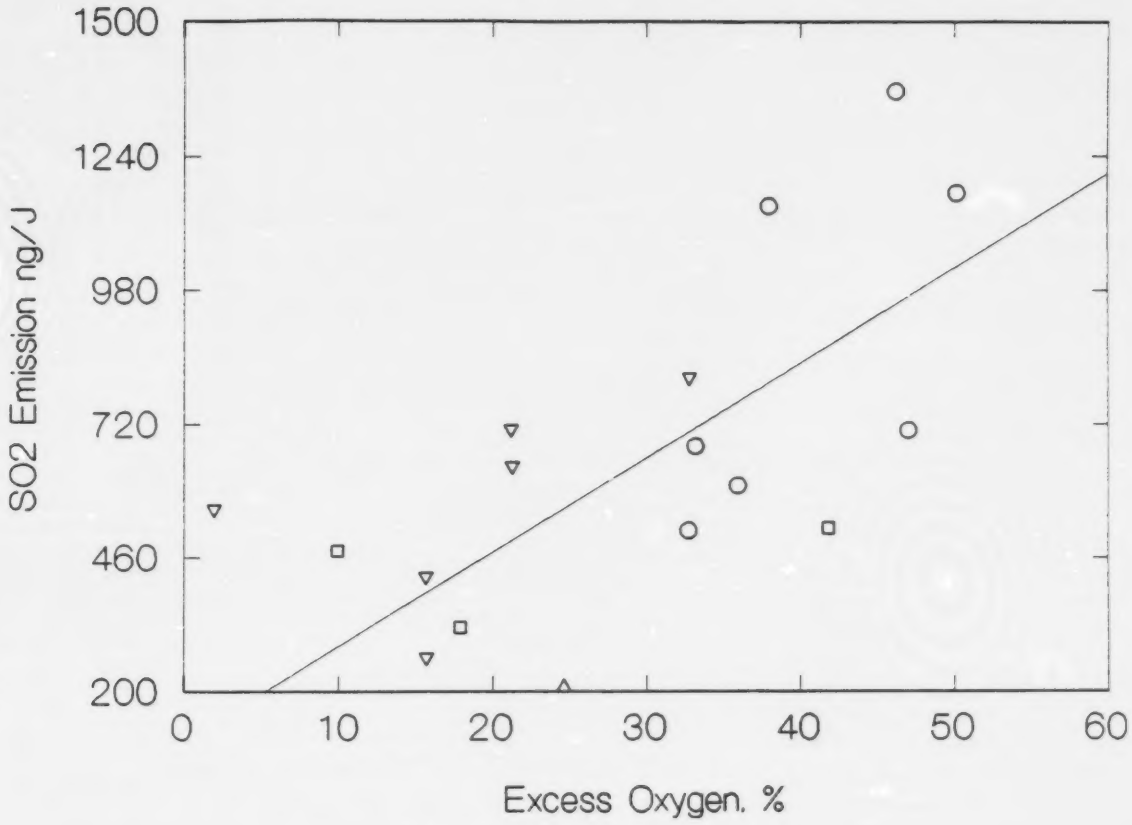

Fig. 21 Effect of excess O_2 level on SO_2 emission of Onakawana lignite.

Legend:
- ○ Mark I bubbling FBC, base line tests
- △ Mark I bubbling FBC, Ca/S = 1.62
- ▽ Mark II bubbling FBC, base line tests
- □ Mark II bubbling FBC, Ca/S = 1.20-1.45

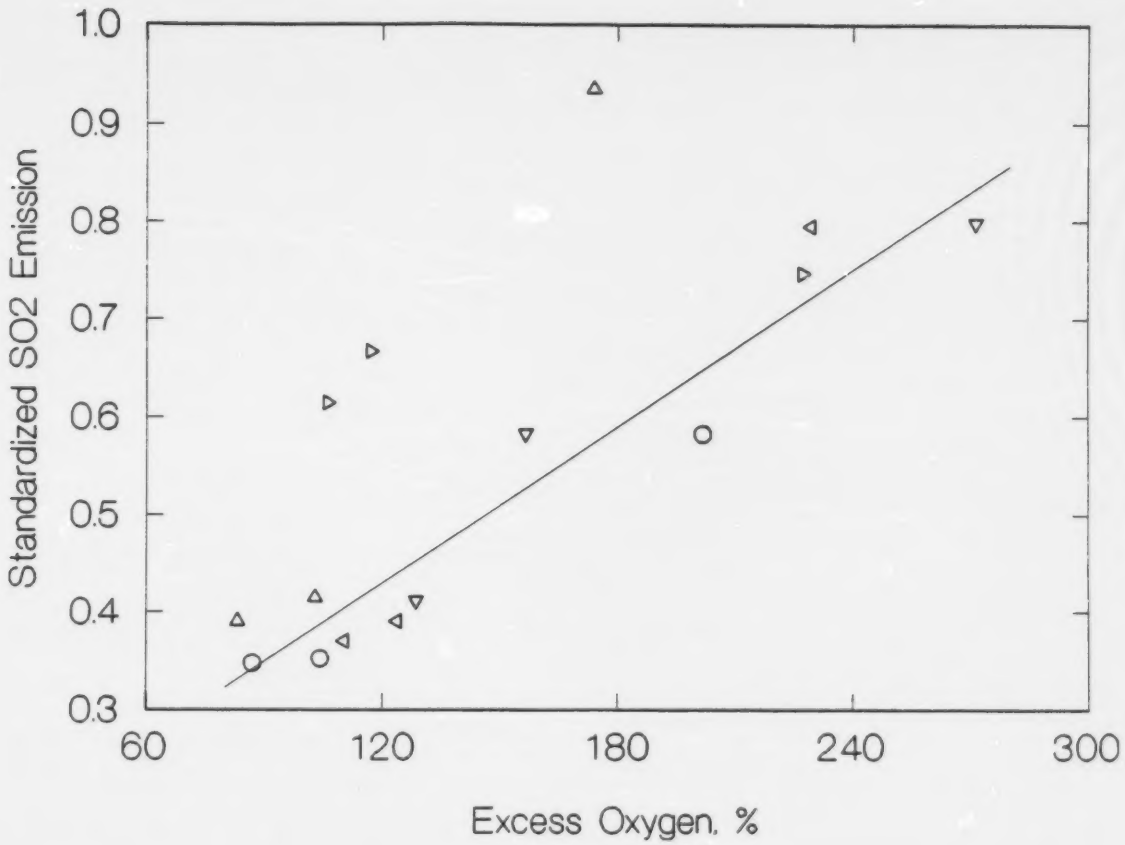

Fig. 22 Effect of excess O_2 on standardized SO_2 emission observed at Summerside heating plant.

Coal: ○ Minto △ Devco ▽ Evans
◁ Brogan ▷ Novaco

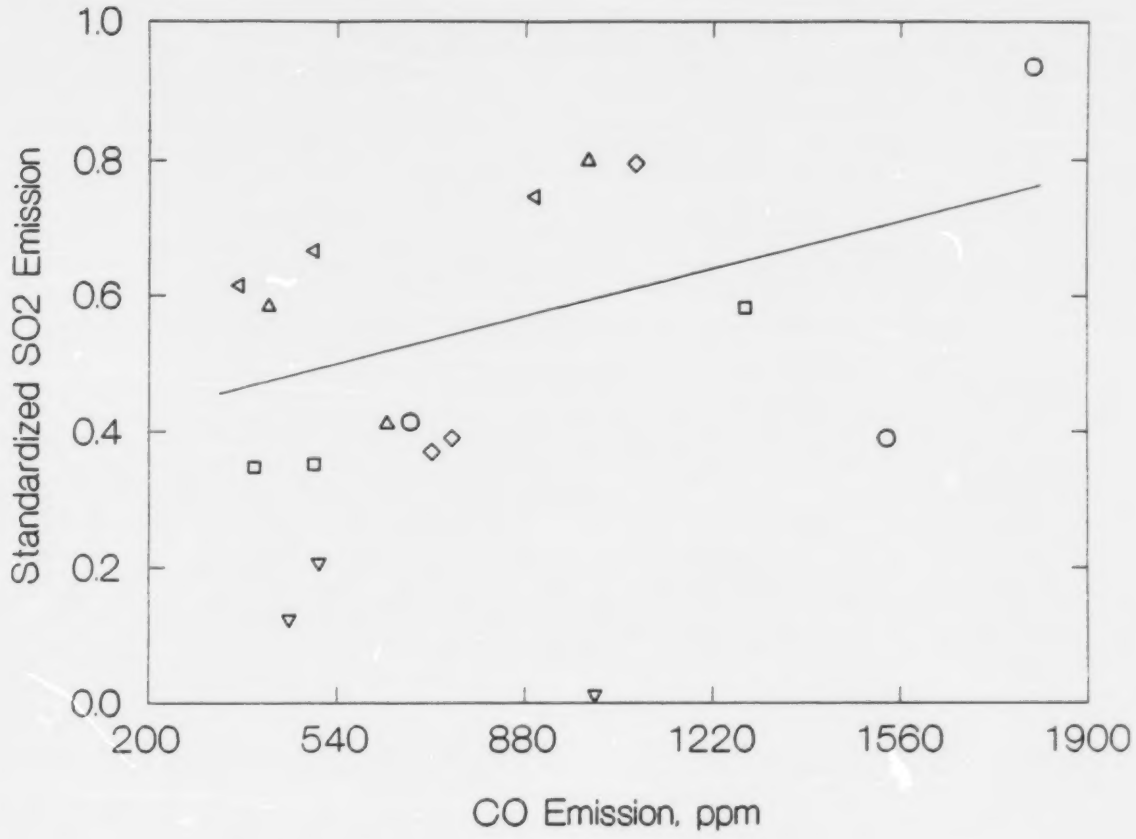

Fig. 23 Effect of CO emission level on standardized SO_2 emission observed at Summerside heating plant.

Coal: △ Evans, CANMET tests ▽ Evans, US EPA tests
□ Minto ○ Devco
◁ Novaco ◇ Brogan

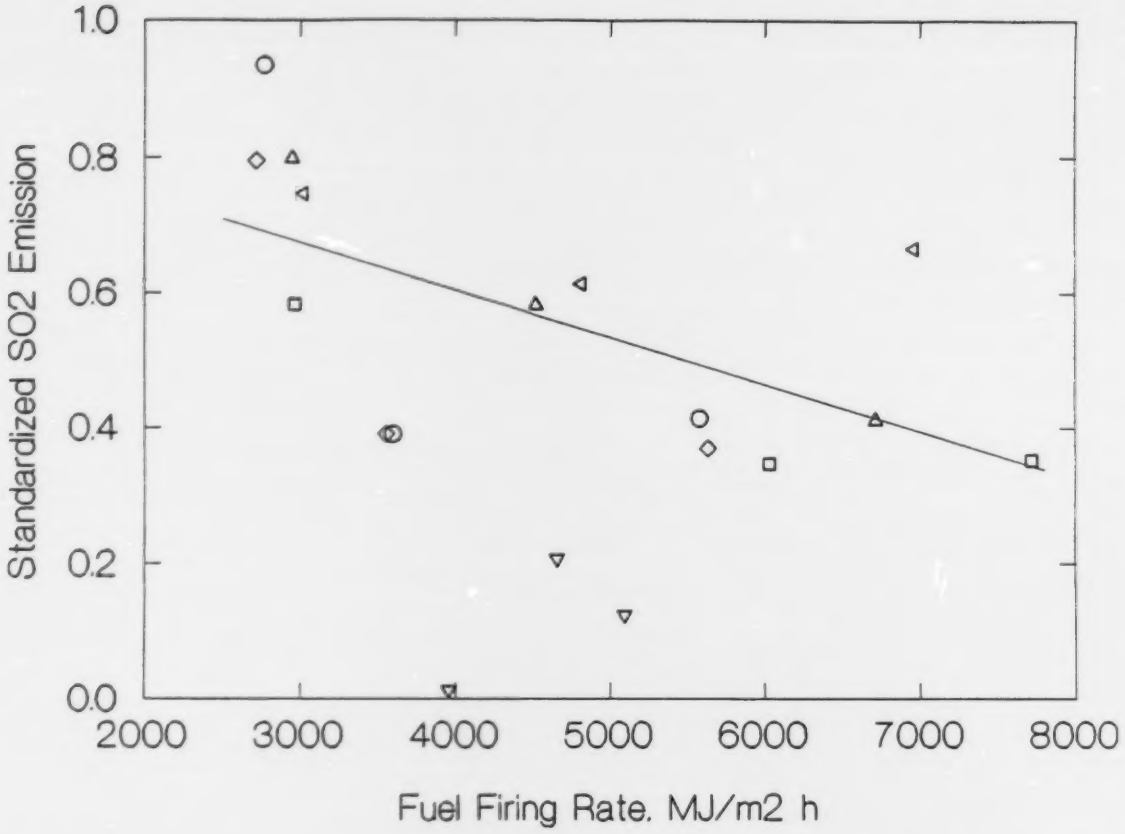

Fig. 24 Effect of fuel firing rate on standardized SO_2 emission observed at Summerside heating plant.

Coal:
- □ Minto
- ◁ Novaco
- △ Evans, CANMET tests
- ○ Devco
- ◇ Brogan
- ▽ Evans, US EPA tests

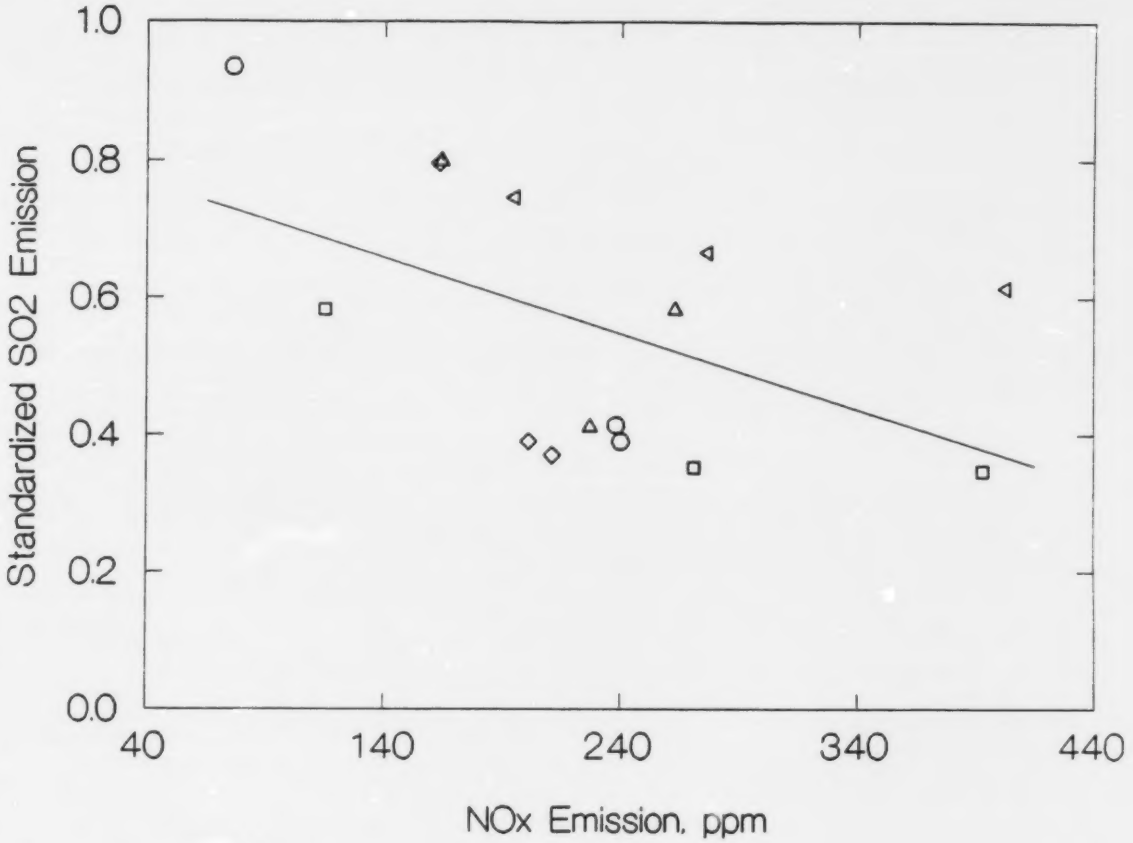

Fig. 25 Effect of NO_x emission level on standardized SO_2 emission observed at Summerside heating plant.

Coal: □ Minto ○ Devco ◁ Novaco
◇ Brogan △ Evans

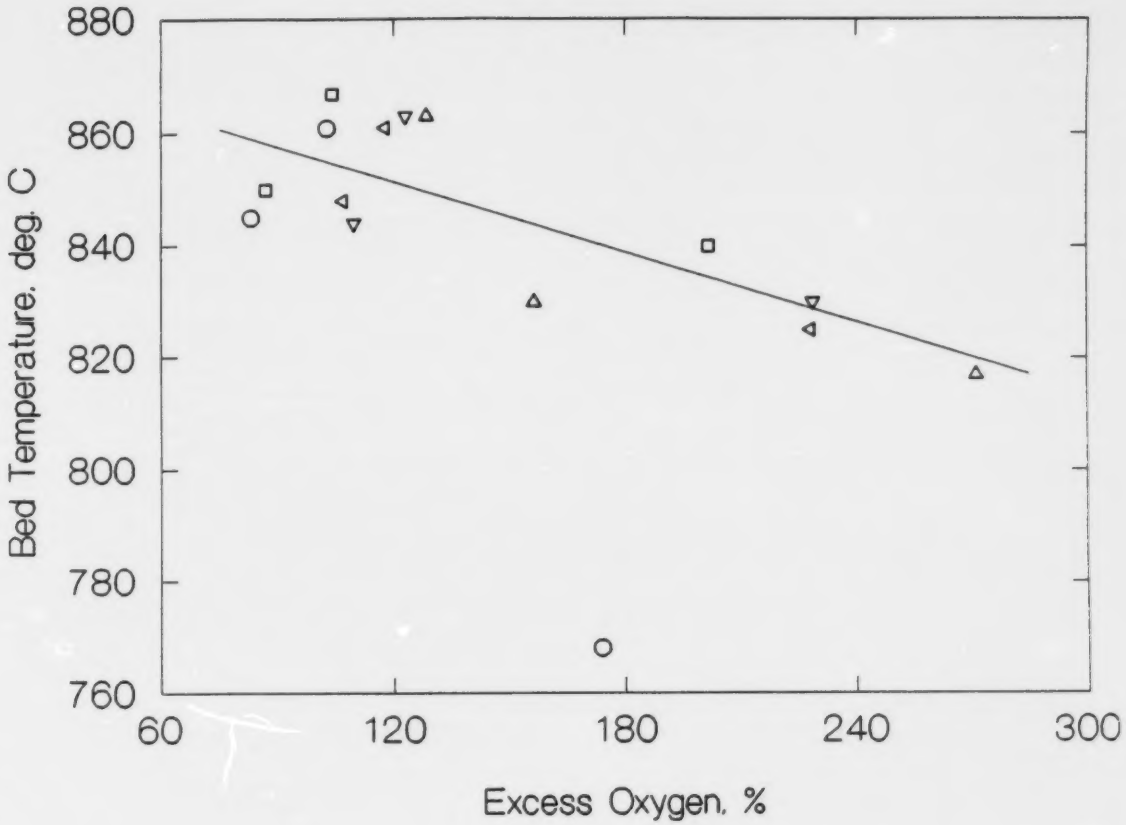

Fig. 26 Effect of excess O_2 level on bed temperature observed at Summerside heating plant.

Coal: □ **Minto** ○ **Devco** ◁ **Novaco** ▽ **Brogan** △ **Evans**

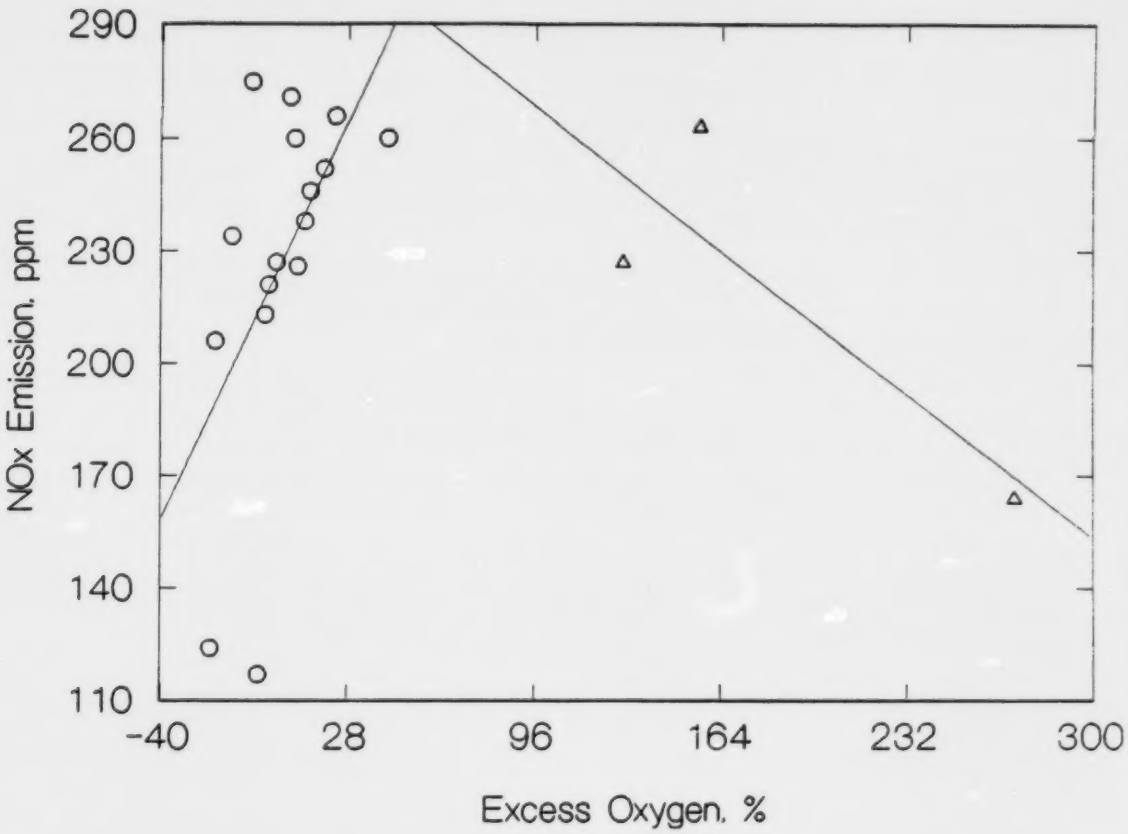

Fig. 27 Effect of excess O_2 level on NO_x concentration in flue gas of Evans coal.

Legend: ○ pilot-plant tests, Queen's Univ. bubbling FBC
△ full-scale tests, Summerside heating plant

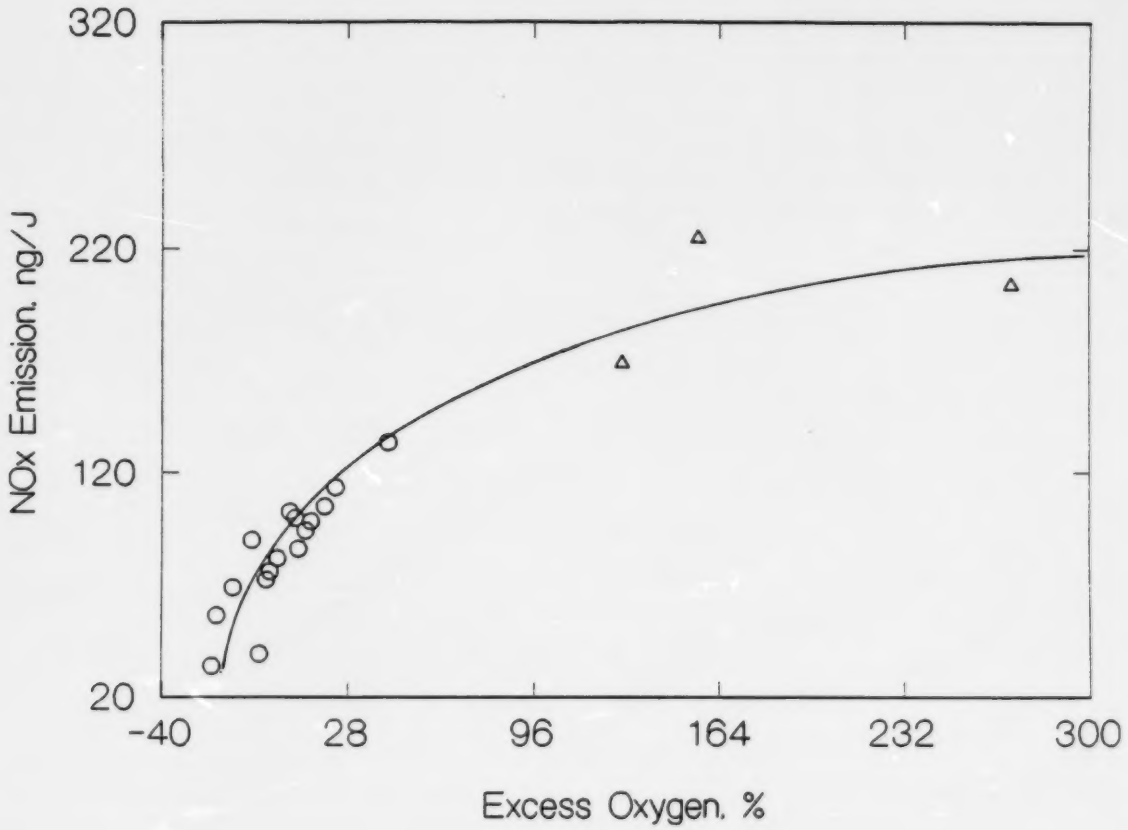

Fig. 28 Effect of excess O_2 level on NO_x emission of Evans coal.

Legend: ○ pilot-plant tests, Queen's Univ. bubbling FBC
△ full-scale tests, Summerside heating plant

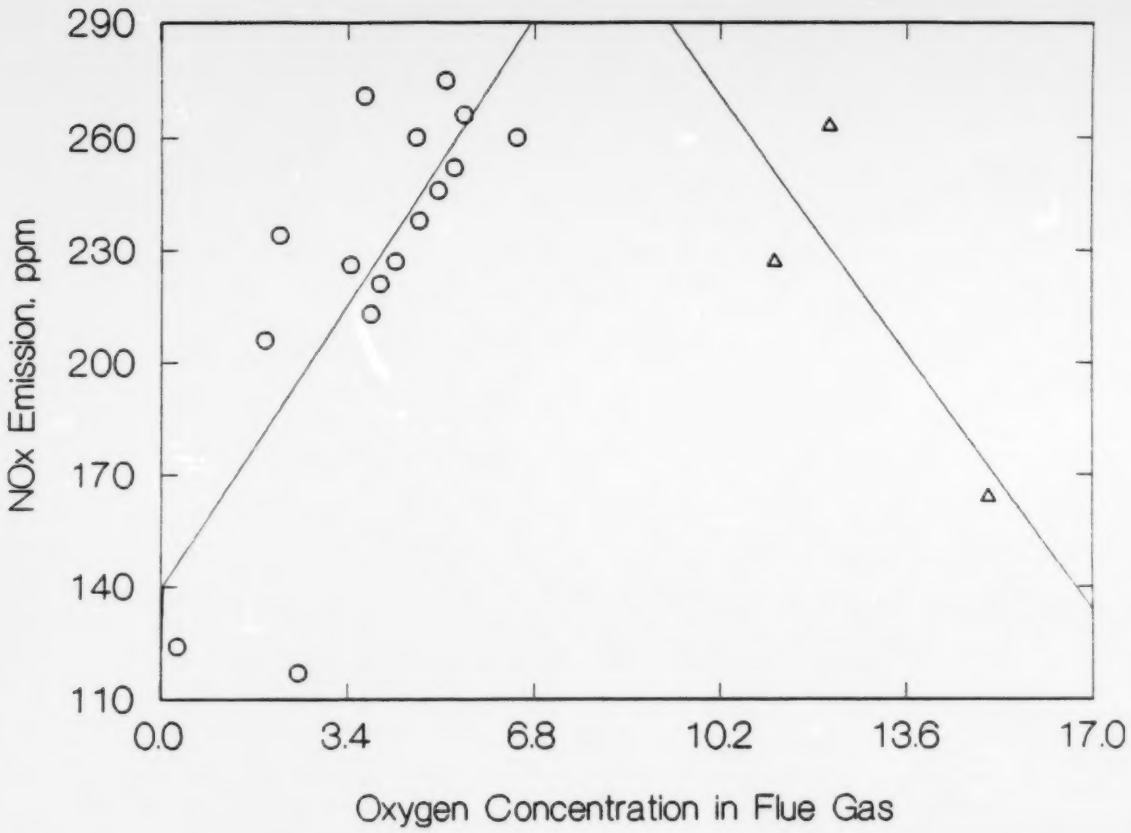

Fig. 29 Variation of NO_x concentration with O_2 concentration in the flue gas of Evans coal.

Legend: ○ pilot-plant tests, Queen's Univ. bubbling FBC
△ full-scale tests, Summerside heating plant

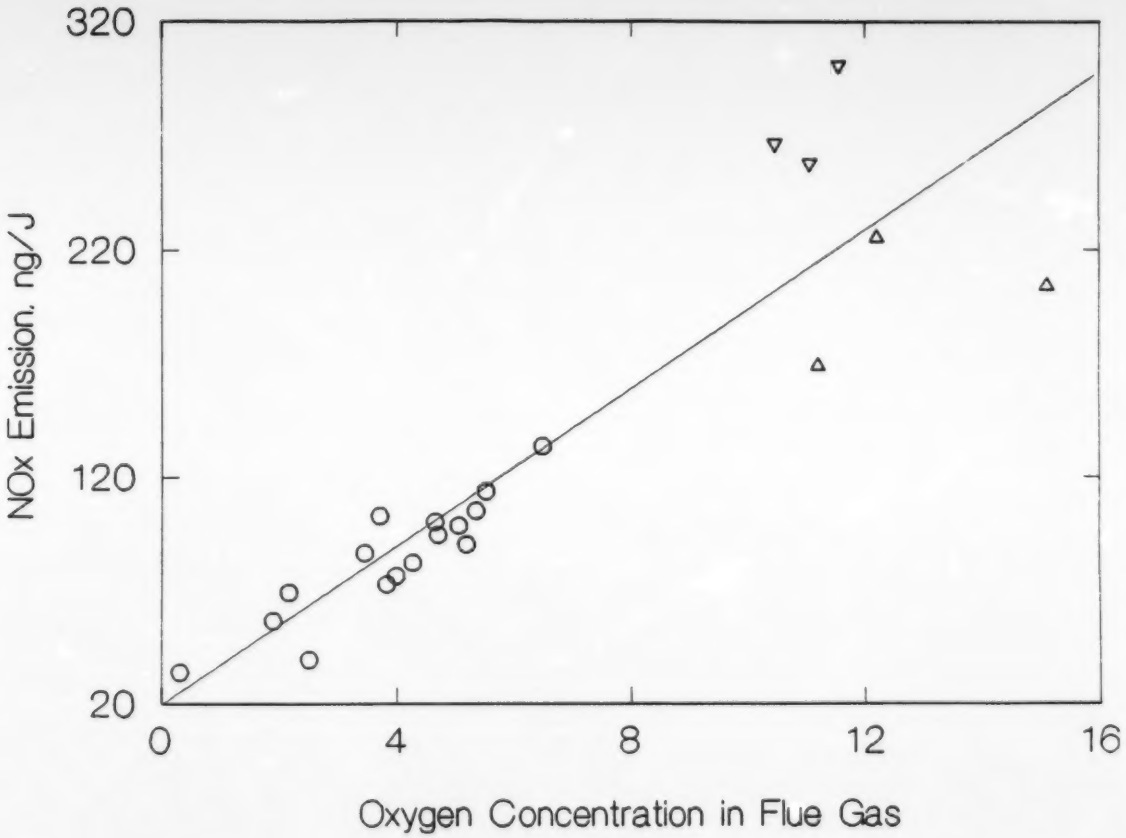

Fig. 30 Effect of O_2 level in flue gas on NO_x emission of Evans coal.

Legend: ○ pilot-plant tests, Queen's Univ. bubbling FBC
△ CANMET full-scale tests, Summerside heating plant
▽ US EPA full-scale tests, Summerside heating plant

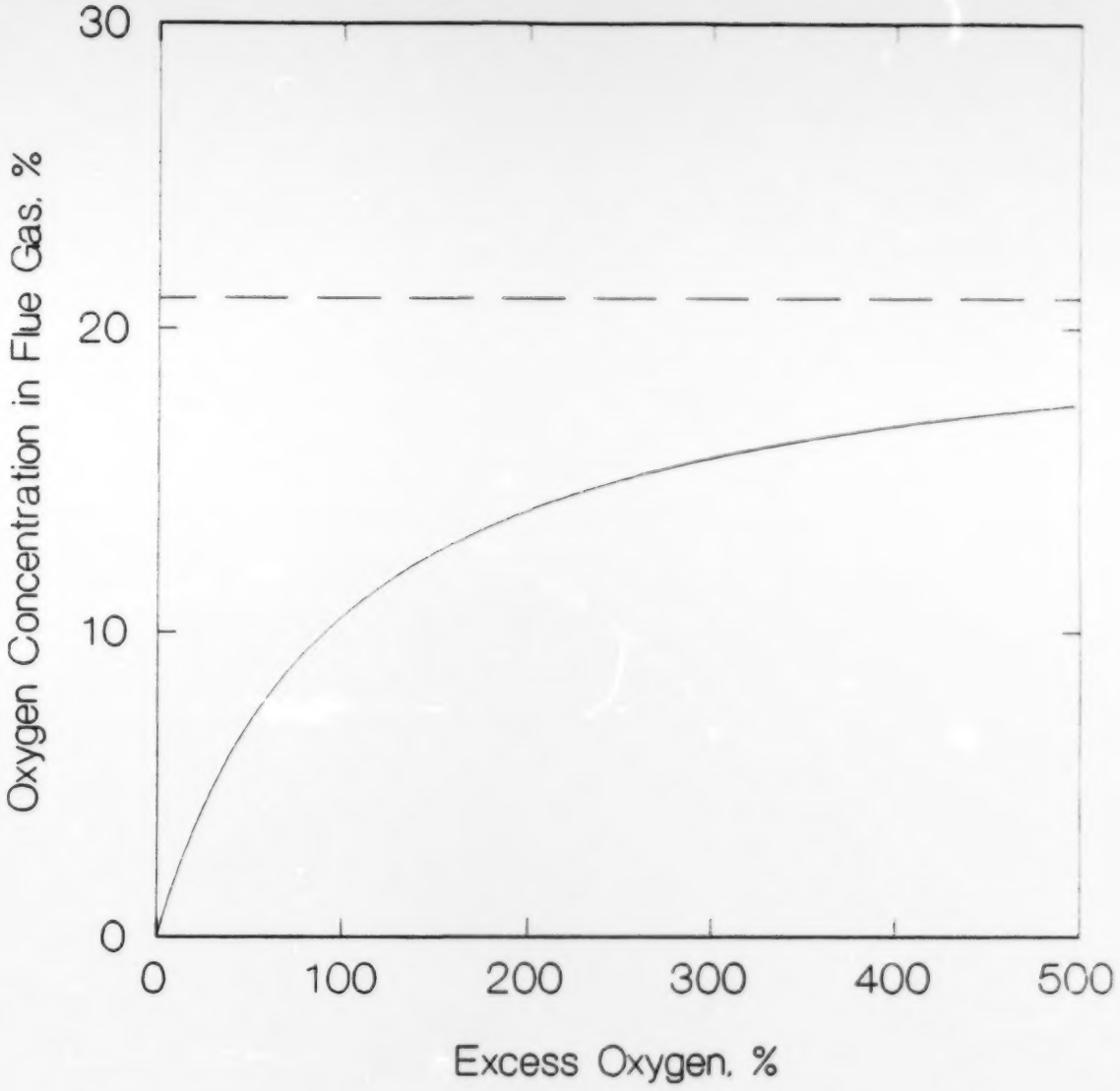

Fig. 31 Relationship between O_2 concentration in flue gas and excess O_2 level.

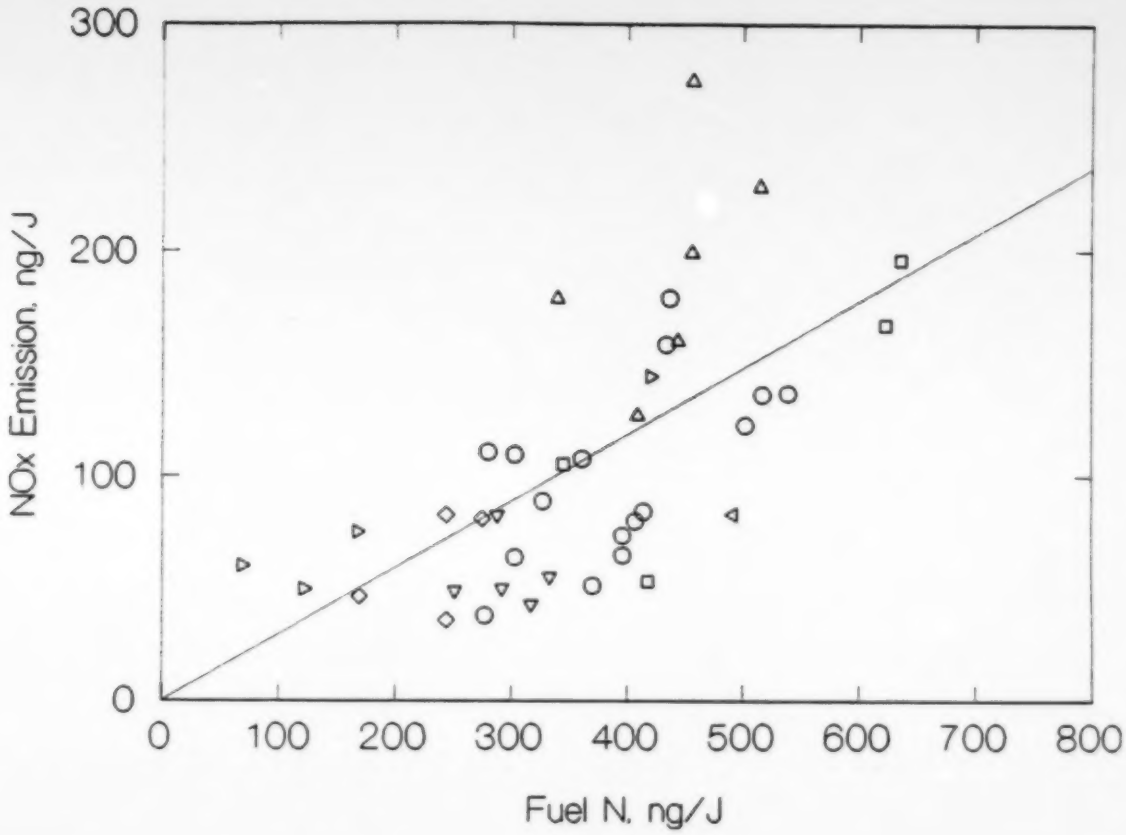

Fig. 32 Effect of fuel N on NO_x emission.

Legend:
- ○ coal, bubbling FBC
- ▽ coal, circulating FBC
- △ coal, Summerside heating plant
- □ petroleum coke, bubbling FBC
- ◁ petroleum coke, circulating FBC
- ▷ liquid fuel, bubbling FBC
- ◇ liquid fuel, circulating FBC

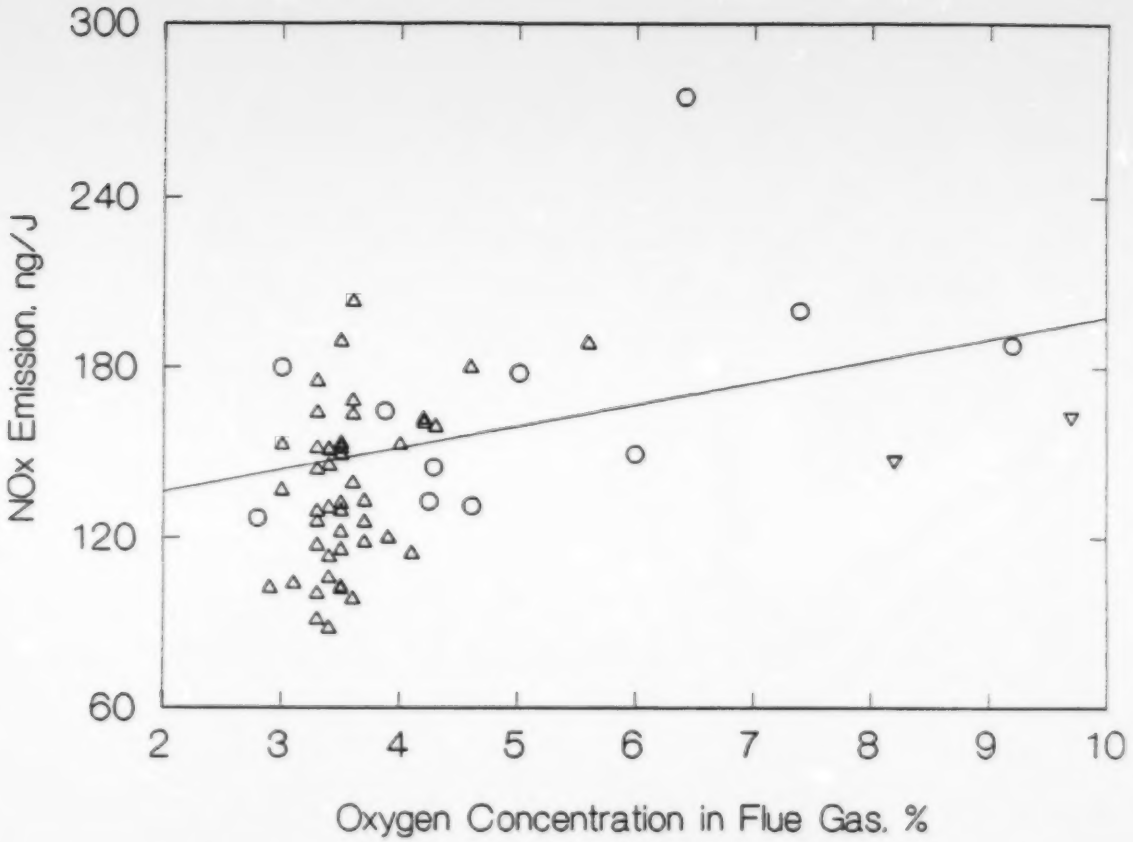

Fig. 33 Effect of O_2 level in flue gas on NO_x emission of Devco coal.

Facility: ○ **Queen's Univ. bubbling FBC**
△ **Mark II bubbling FBC**
▽ **Summerside heating plant**

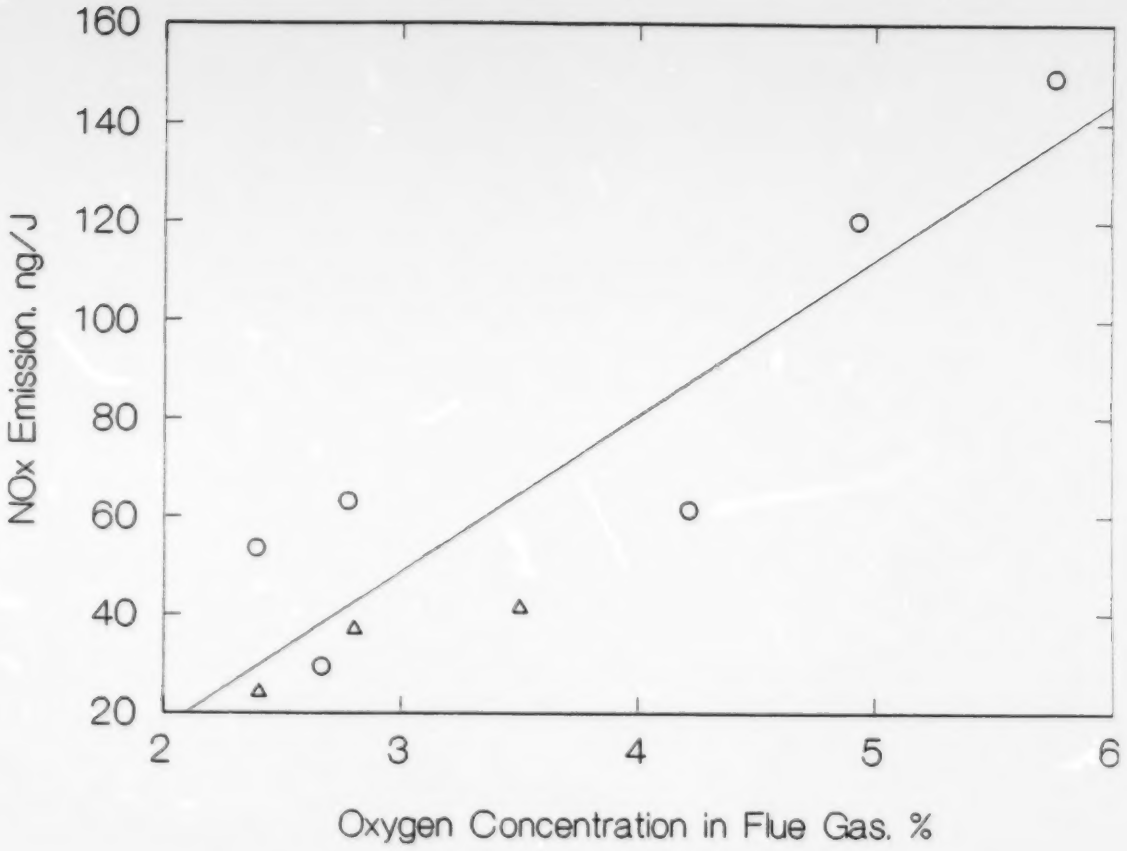

Fig. 34 Effect of O_2 level in flue gas on NO_x emission of Mt Klappan coal.

Facility: ○ Queen's Univ. bubbling FBC
△ UBC circulating FBC

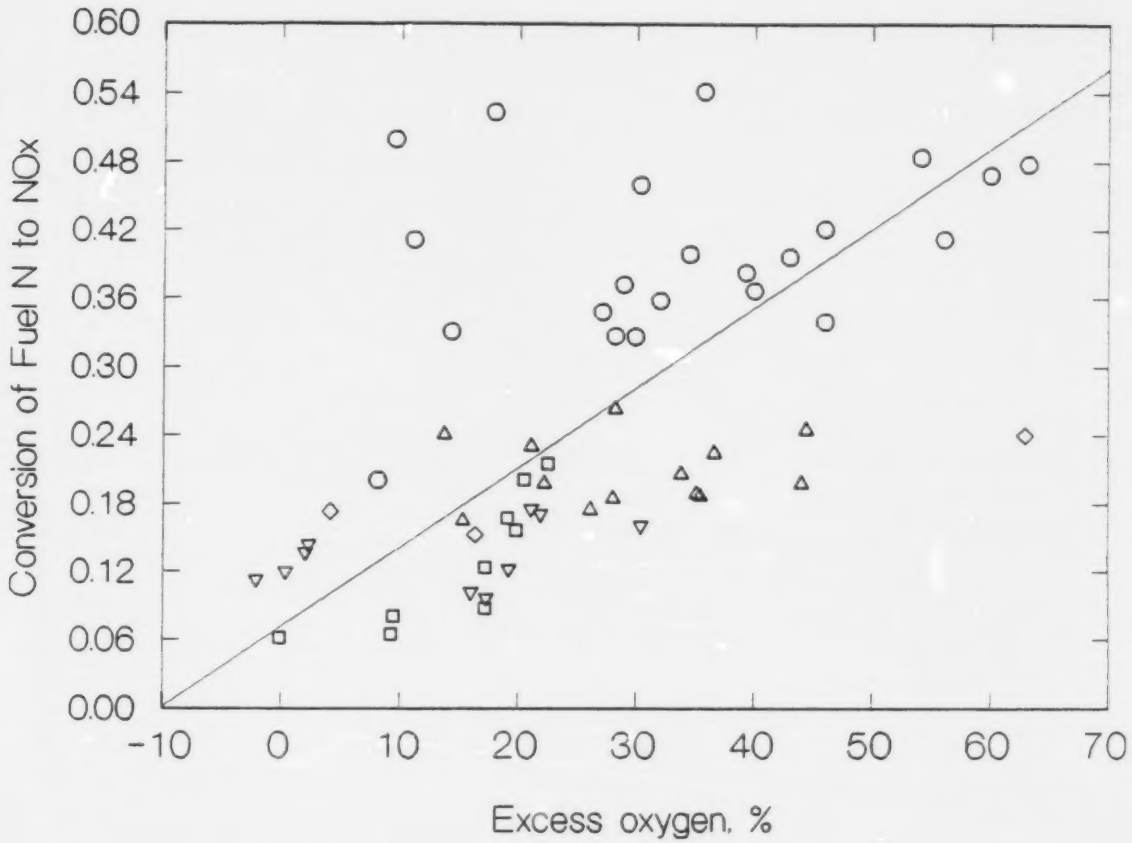

Fig. 35 Effect of excess O_2 level on conversion of fuel N to NO_x of heavy oils.

Legend:
- ○ #6 oil, Mark II bubbling FBC
- △ CANMET pitch, Mark II bubbling FBC
- ▽ CANMET pitch, UBC circulating FBC
- □ H-oil pitch, UBC circulating FBC
- ◇ Bitumen, Mark II bubbling FBC

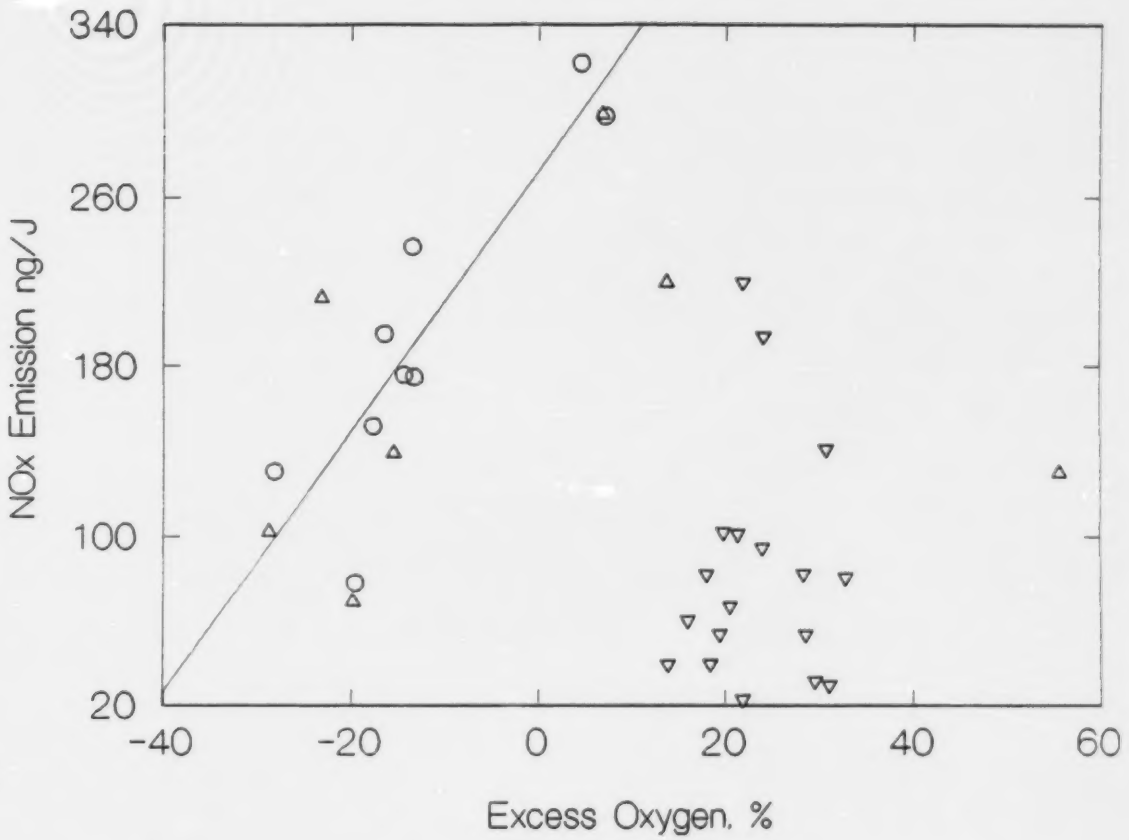

Fig. 36 Effect of excess O_2 level on NO_x emission of Syncrude coke.

Facility: ○ Queen's Univ. bubbling FBC
△ Mark II bubbling FBC
▽ circulating FBC in Finland.

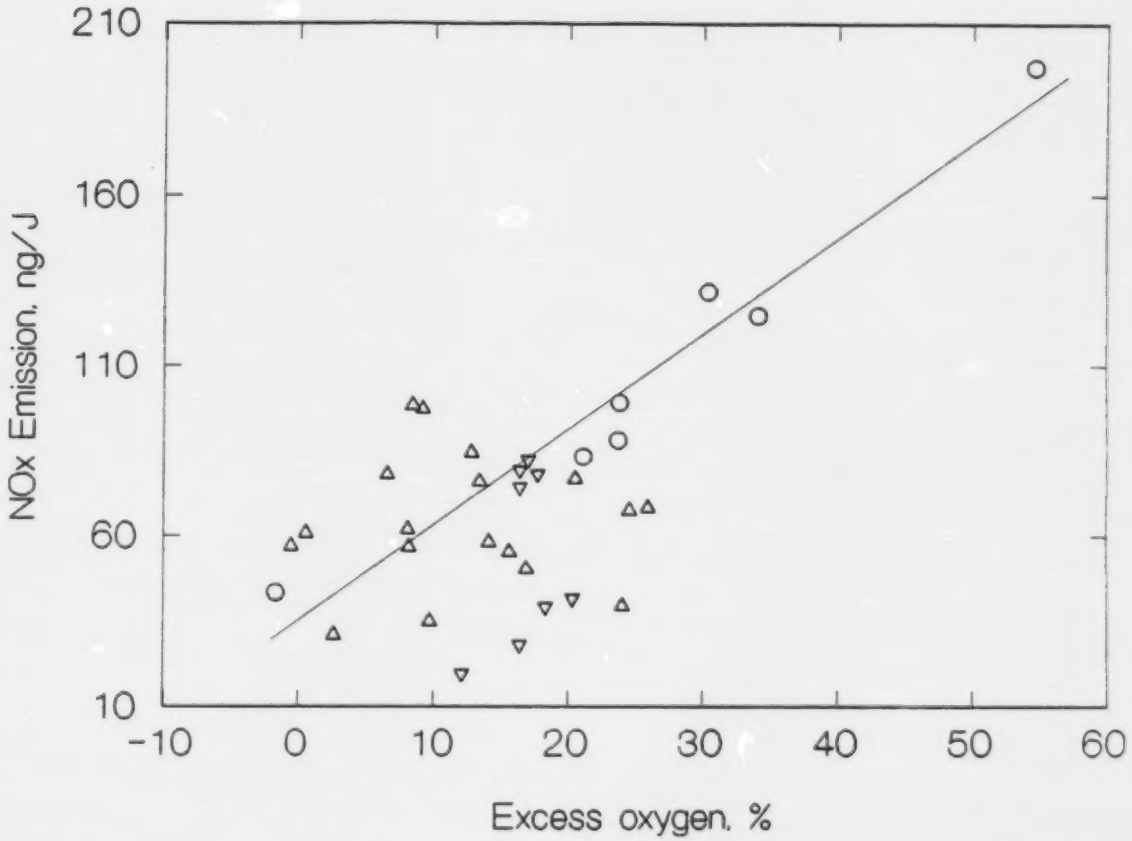

Fig. 37 Effect of excess O_2 level on NO_x emission of Highvale coal.

Facility:
- ○ Queen's Univ. bubbling FBC
- △ Mark I bubbling FBC
- ▽ UBC circulating FBC

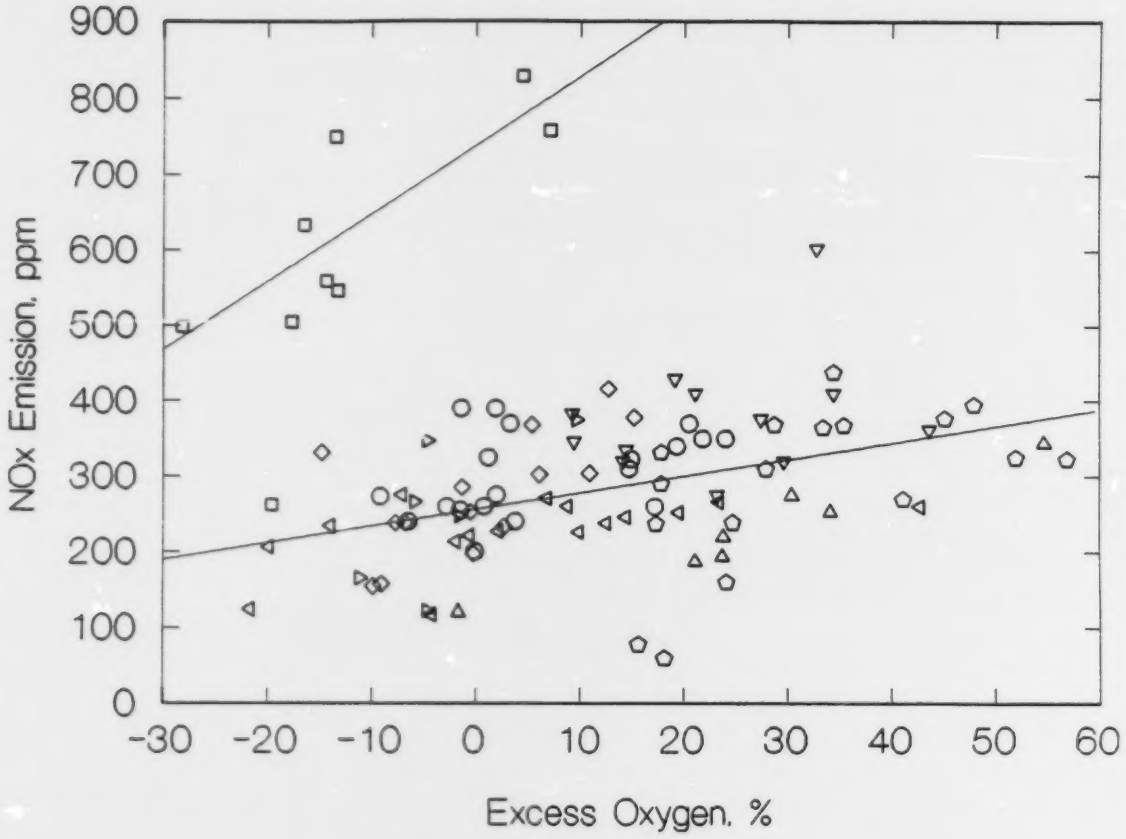

Fig. 38 Effect of excess O_2 level on NO_x concentration in flue gas observed at Queen's Univ. bubbling FBC pilot plant.

Fuel:
- ○ Minto coal
- ◁ Evans coal
- ▽ Devco coal
- □ Syncrude coke
- ▷ Mt Klappan coal
- △ Highvale coal
- ⬡ coal/water slurry
- ◇ Saskatchewan Petroleum coke

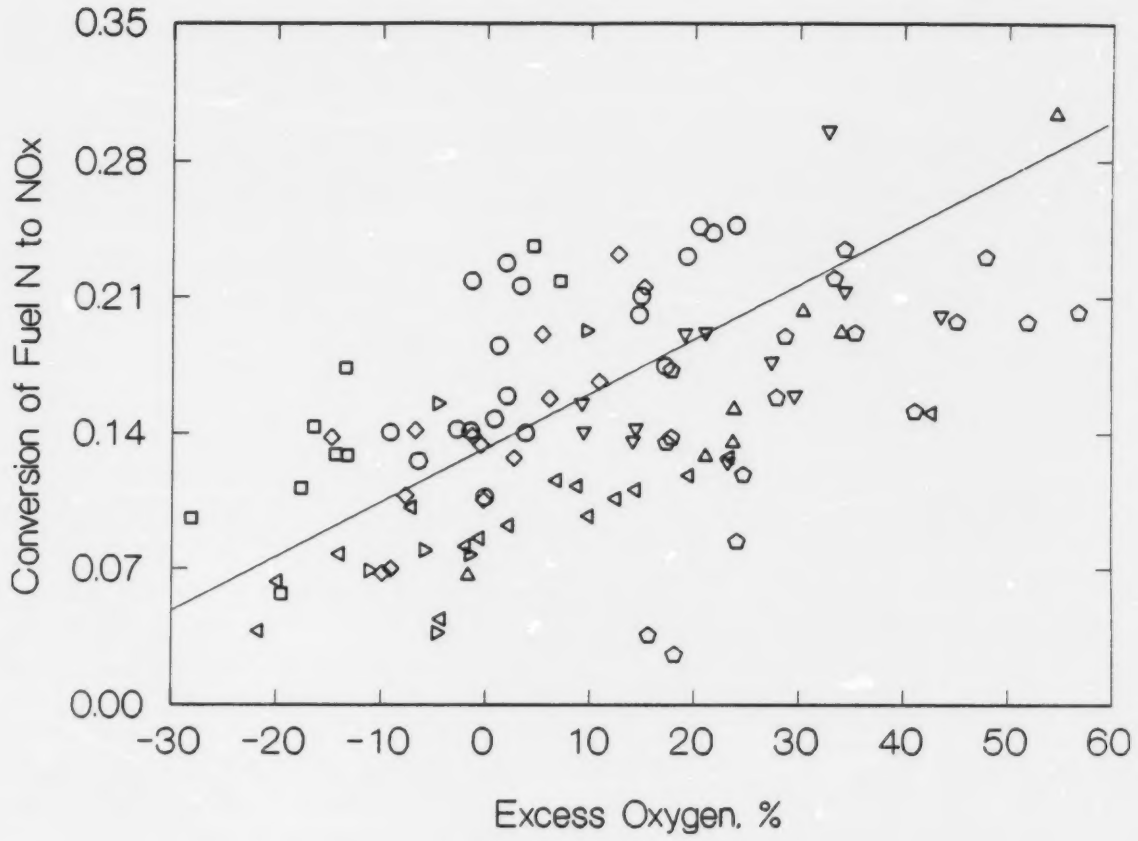

Fig. 39 Effect of O_2 level in flue gas on conversion of fuel N to NO_x observed at Queen's Univ. bubbling FBC pilot plant.

Fuel:
- ◁ Evans coal
- ○ Minto coal
- ▽ Devco coal
- □ Syncrude coke
- △ Highvale coal
- ▷ Mt. Klappan coal
- ⬠ coal/water slurry
- ◇ Saskatchewan Petroleum coke

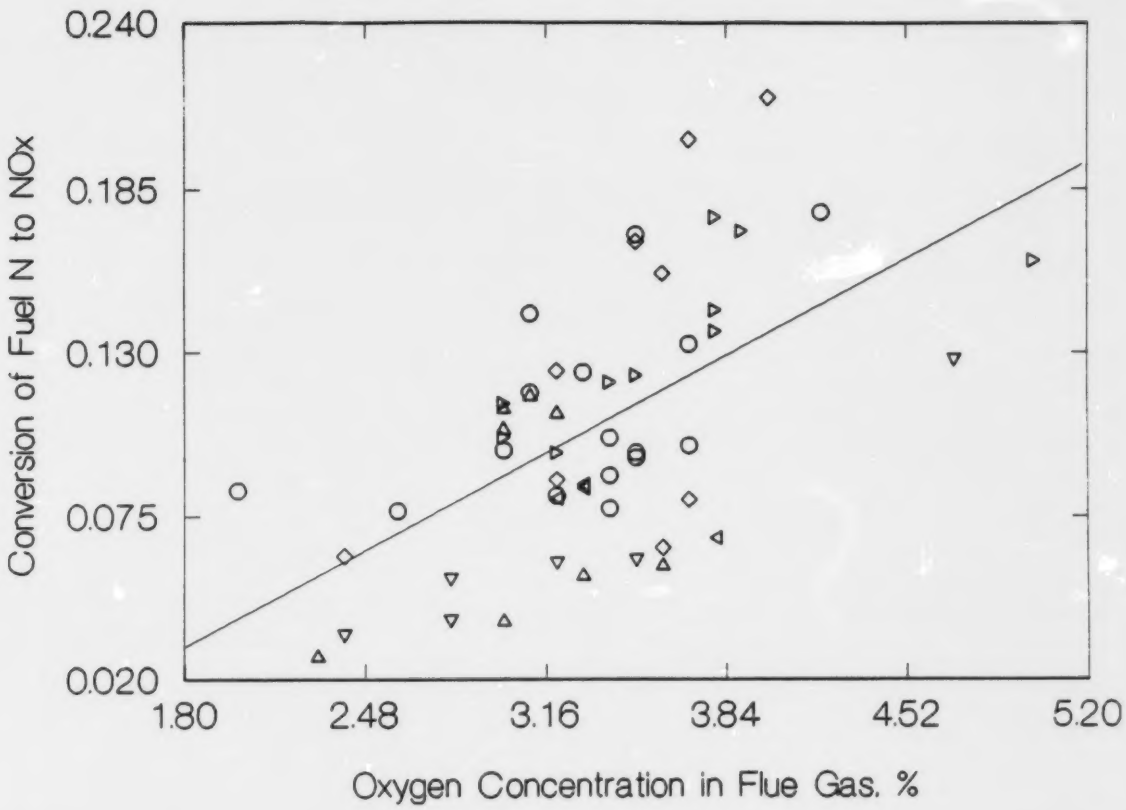

Fig. 40 Effect of O_2 level in flue gas on conversion of fuel N to NO_x observed at UBC circulating FBC pilot plant.

Fuel:
- ○ Minto coal
- ▽ Mt Klappan coal
- ▷ CANMET pitch
- △ Highvale coal
- ◁ Poplar River lignite
- □ H-oil pitch

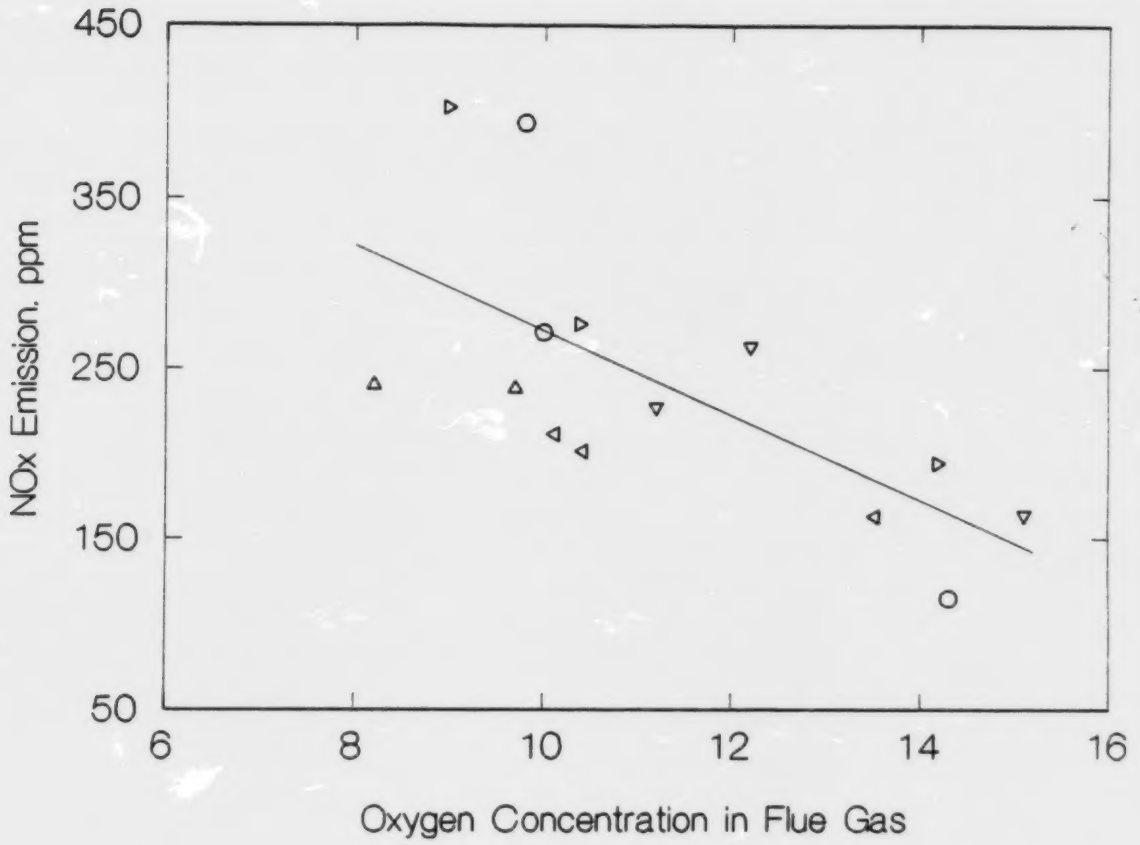

Fig. 41 Correlation between the concentrations of NO_x and O_2 in flue gas observed at Summerside heating plant.

Coal: ○ Minto △ Devco ▽ Evans
◁ Brogan ▷ Novaco

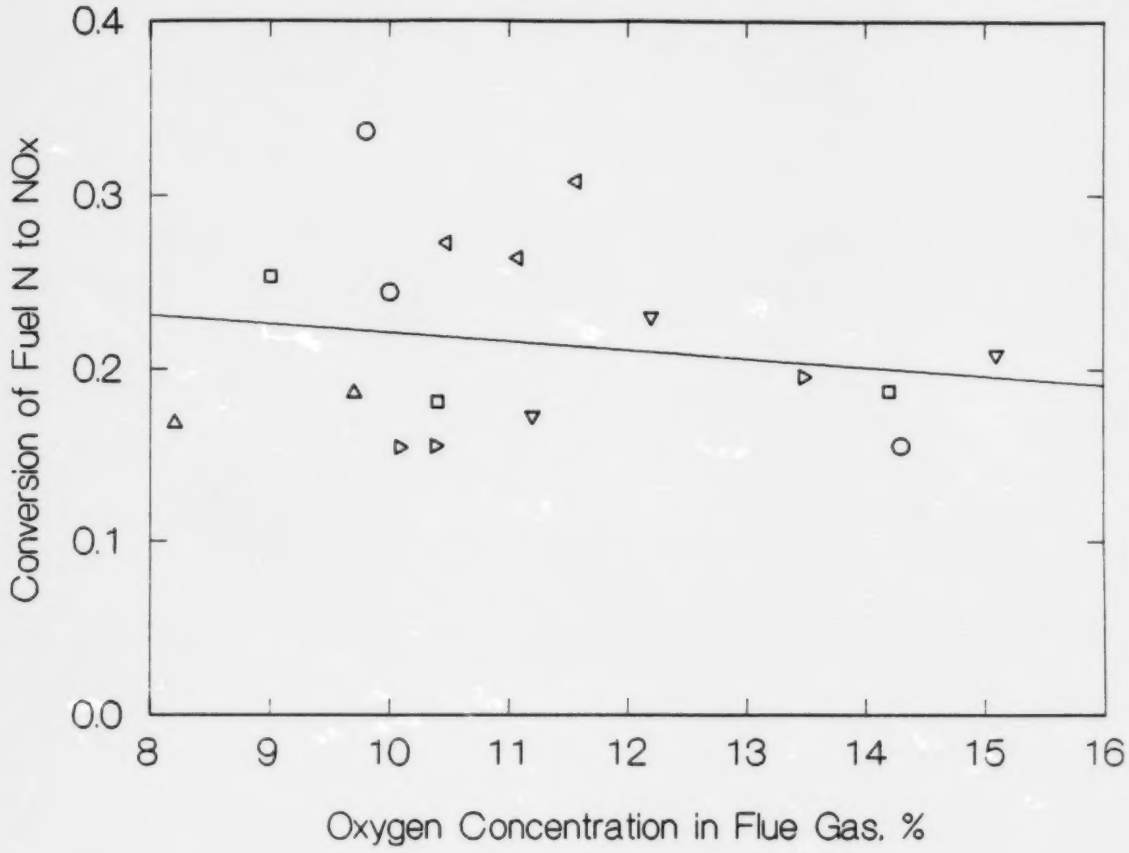

Fig. 42 Effect of O_2 level in flue gas on conversion of fuel N to NO_x observed at Summerside heating plant.

Coal:

- ○ Minto
- ▷ Brogan
- □ Novaco
- △ Devco
- ▽ Evans, CANMET test
- ◁ Evans, US EPA tests

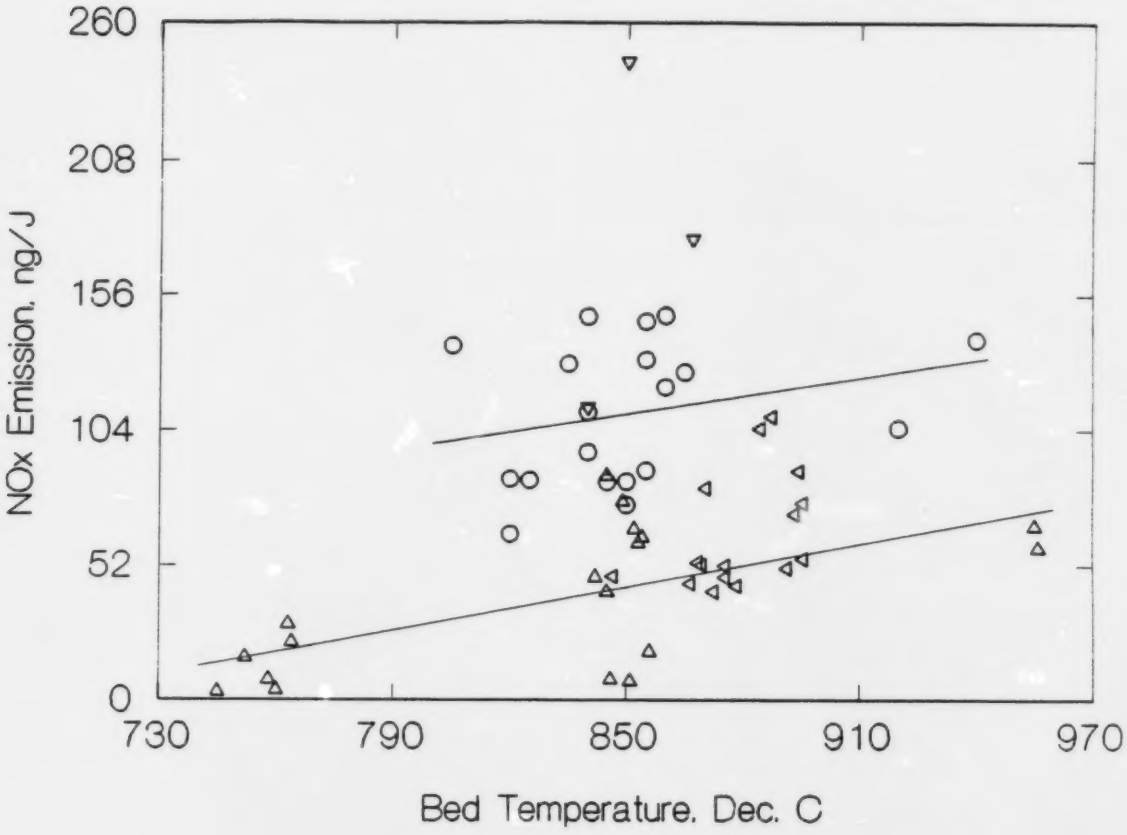

Fig.43 Effect of bed temperature on NO_x emission of Minto coal.

Facility:
- ○ Queen's Univ. bubbling FBC
- △ Mark I bubbling FBC
- ▽ Summerside heating plant
- ◁ UBC circulating FBC

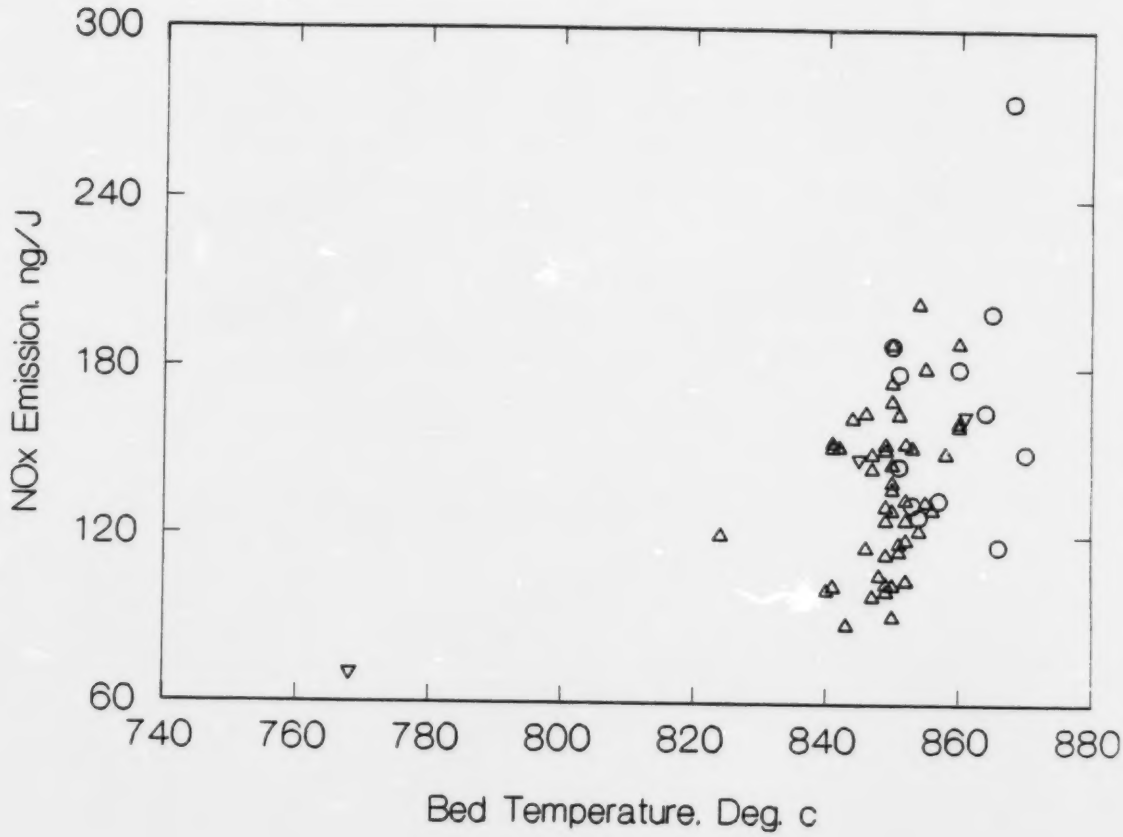

Fig. 44 Effect of bed temperature on NO_x emission of Devco coal.

Facility:
- ○ Queen's Univ. bubbling FBC
- △ Mark II bubbling FBC
- ▽ Summerside heating plant

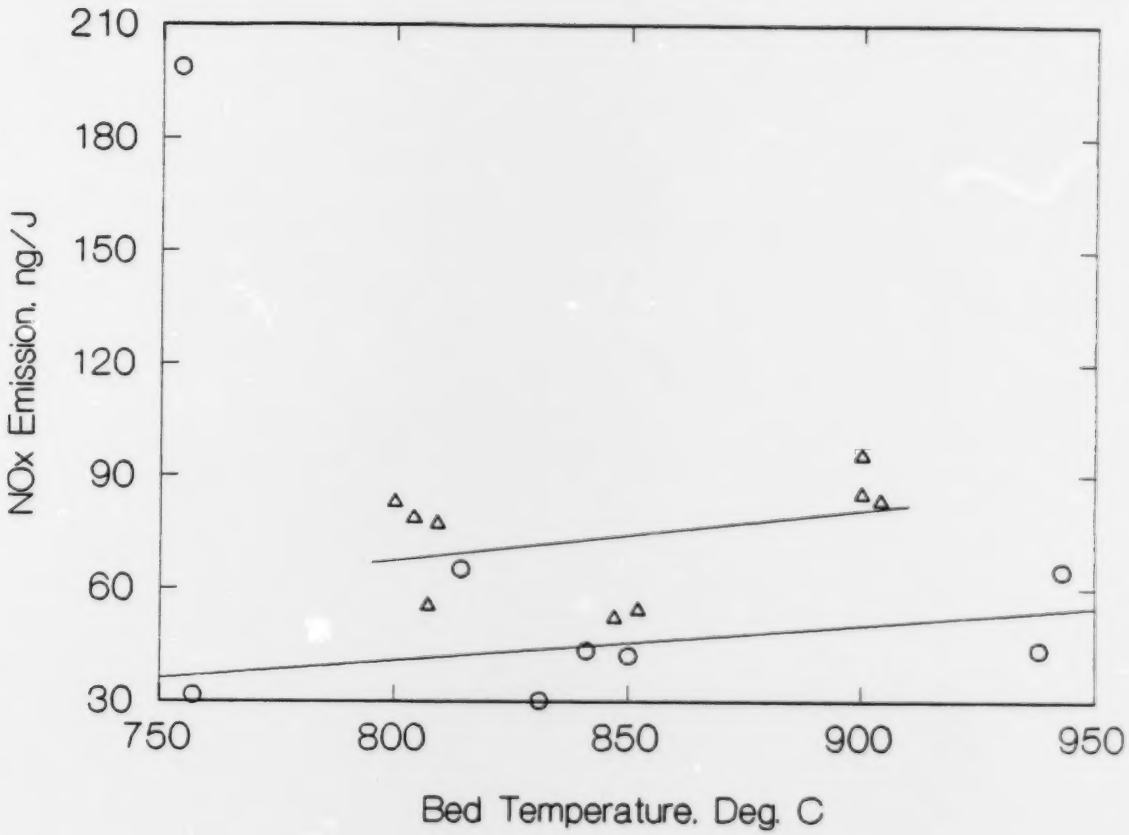

Fig. 45 Effect of bed temperature on NO_x emission of Onakawana lignite.

Facility: ○ Mark I bubbling FBC
△ Mark II bubbling FBC

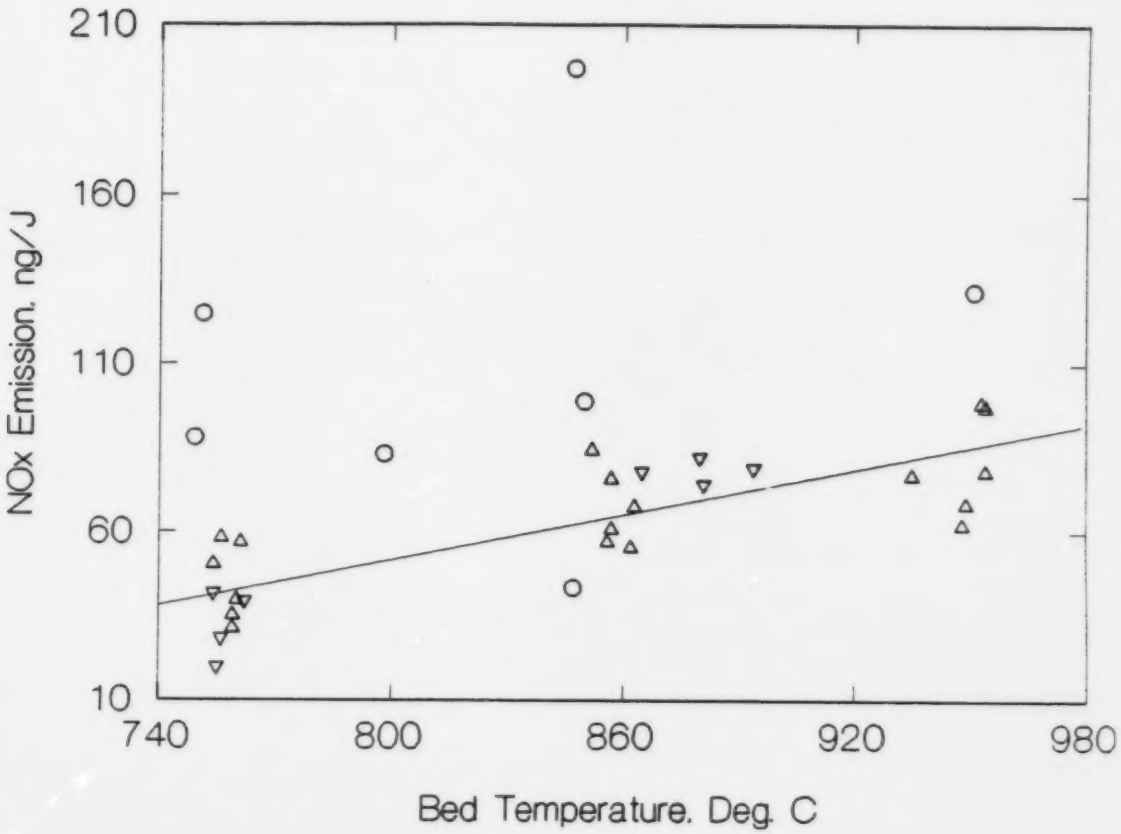

Fig. 46 Effect of bed temperature on NO_x emission of Highvale coal.

Facility:
- ○ **Queen's Univ. bubling FBC**
- △ **Mark I bubbling FBC**
- ▽ **UBC circulating FBC**

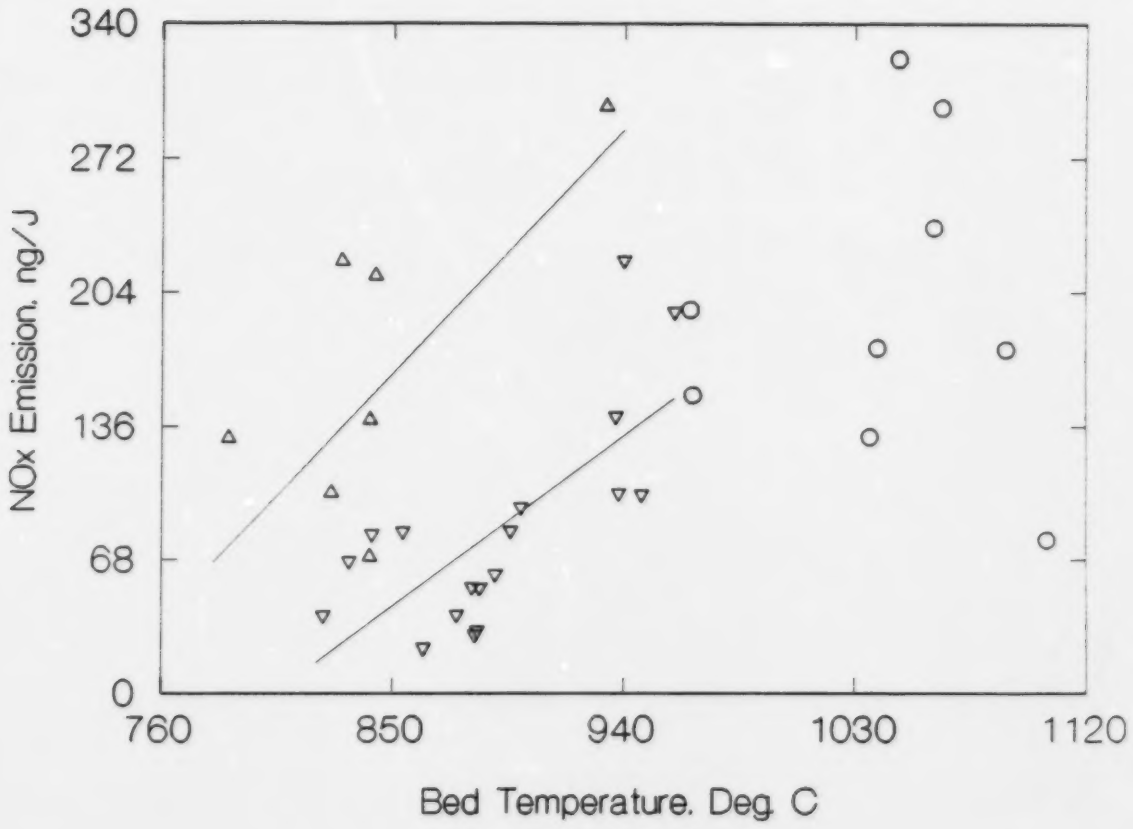

Fig. 47 Effect of bed temperature on NO_x emission of Syncrude coke.

Facility:
- ○ Queen's Univ. bubbling FBC
- △ Mark II bubbling FBC
- ▽ circulating FBC in Finland

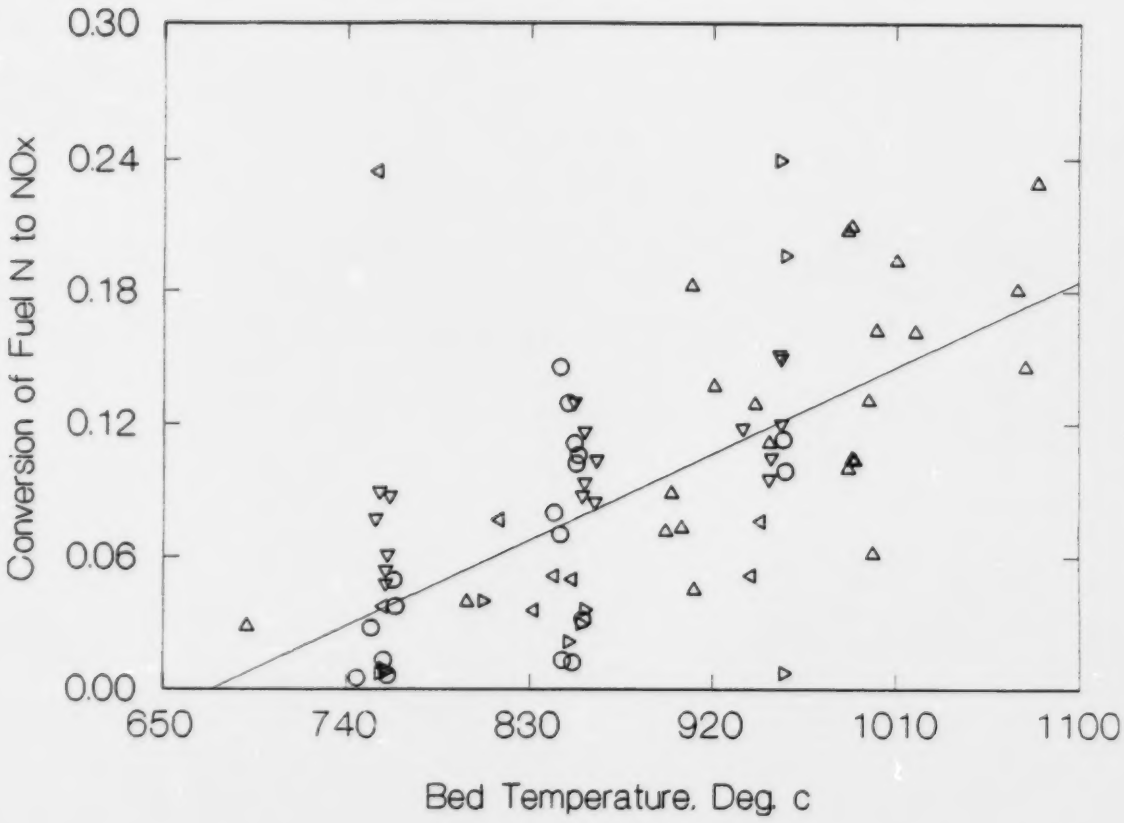

Fig. 48 Effect of bed temperature on conversion of fuel N to NO_x observed at Mark I bubbling FBC pilot plant.

Fuel:
- ○ Minto coal
- ▽ Highvale coal
- ▷ Suncor coke
- △ Line Creek coal
- ◁ Onakawana lignite

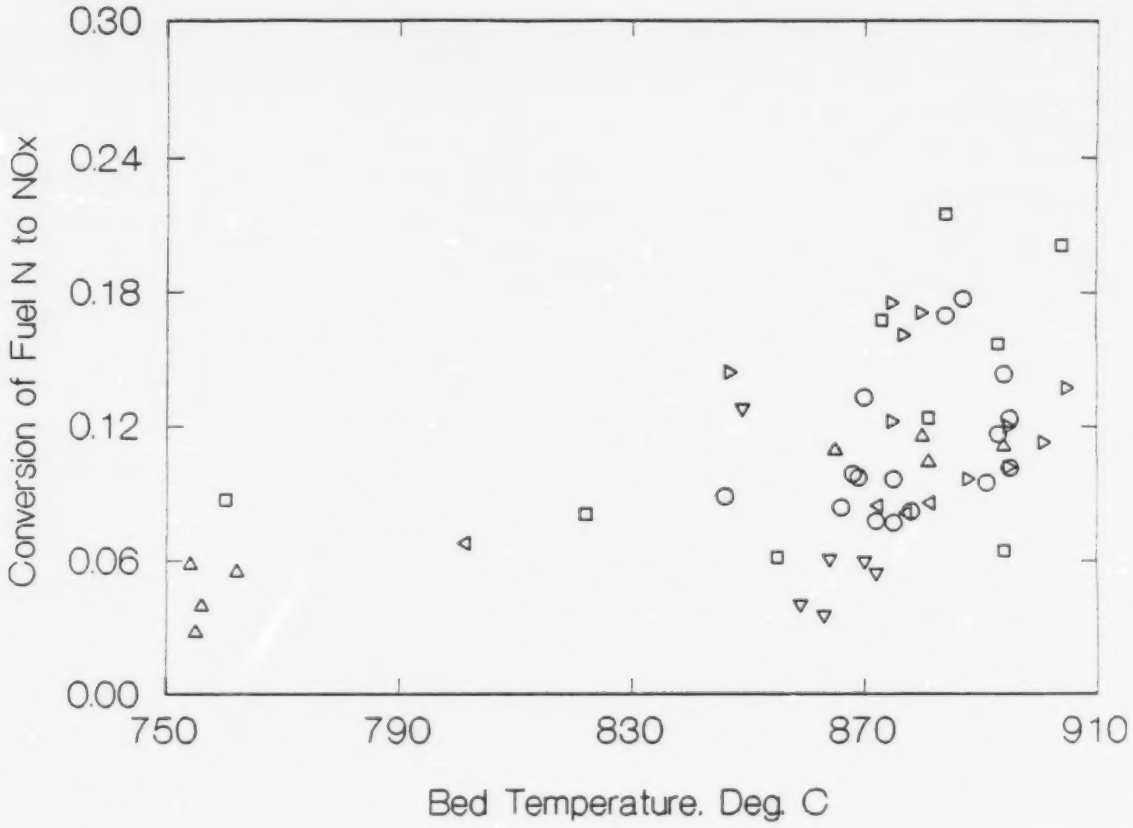

Fig. 49 Effect of bed temperature on conversion of fuel N to NO_x observed at UBC circulating FBC pilot plant.

Fuel:
- ○ Minto coal
- △ Highvale coal
- ▽ Mt Klappan coal
- ◁ Poplar River lignite
- ▷ CANMET pitch
- □ H-oil pitch

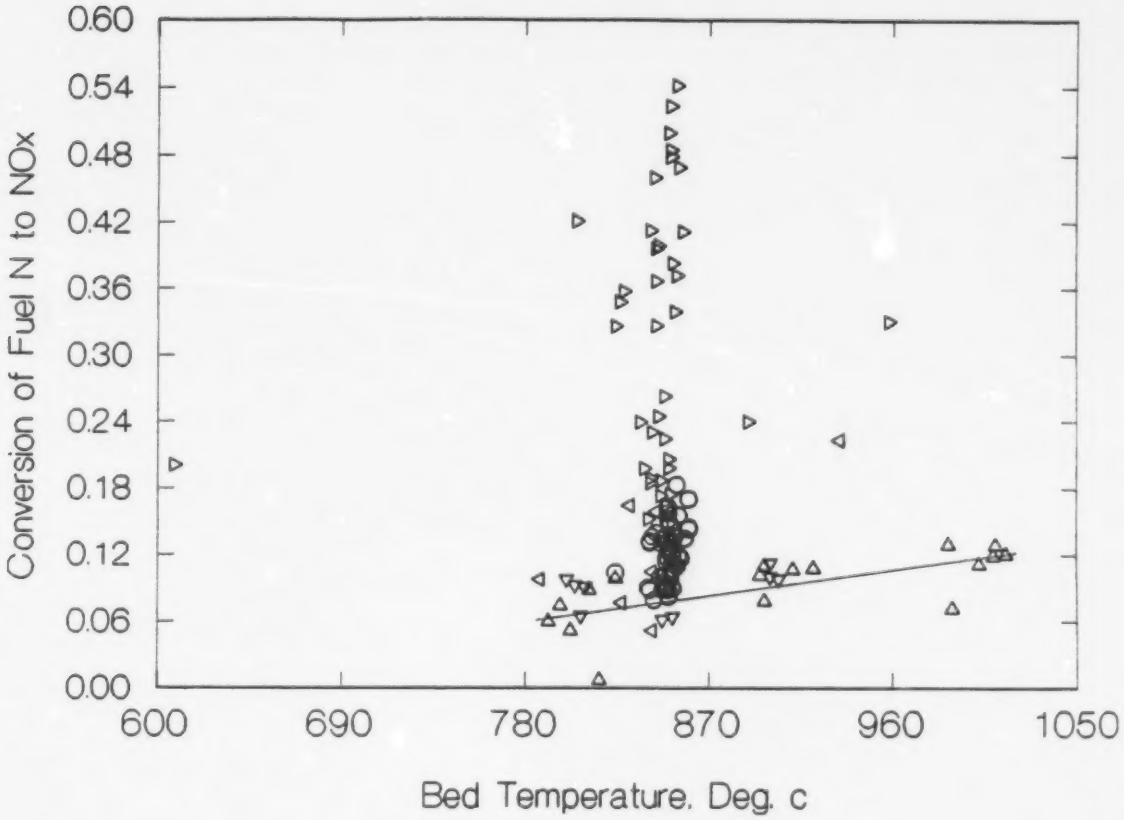

Fig. 50 Effect of bed temperature on NO_x emission observed at Mark II bubbling FBC.

Fuel:
- ○ Devco coal
- △ Byron Creek coal
- ▽ Onakawana lignite
- ▷ Heavy oil
- ◁ Syncrude coke

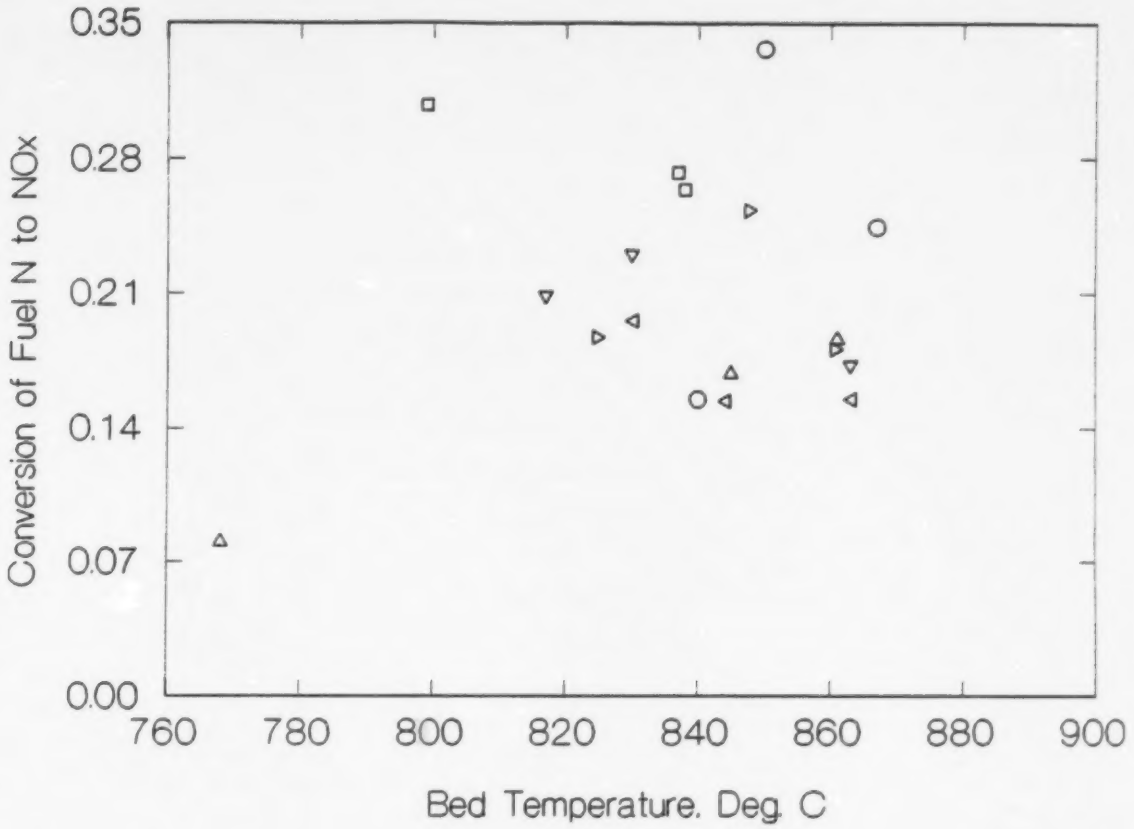

Fig. 51 Effect of bed temperature on conversion of fuel N to NO_x observed at Summerside heating plant.

Coal:
- ○ Minto
- △ Devco
- ◁ Brogan
- ▷ Novaco
- ▽ Evans, CANMET tests
- □ Evans, US EPA tests

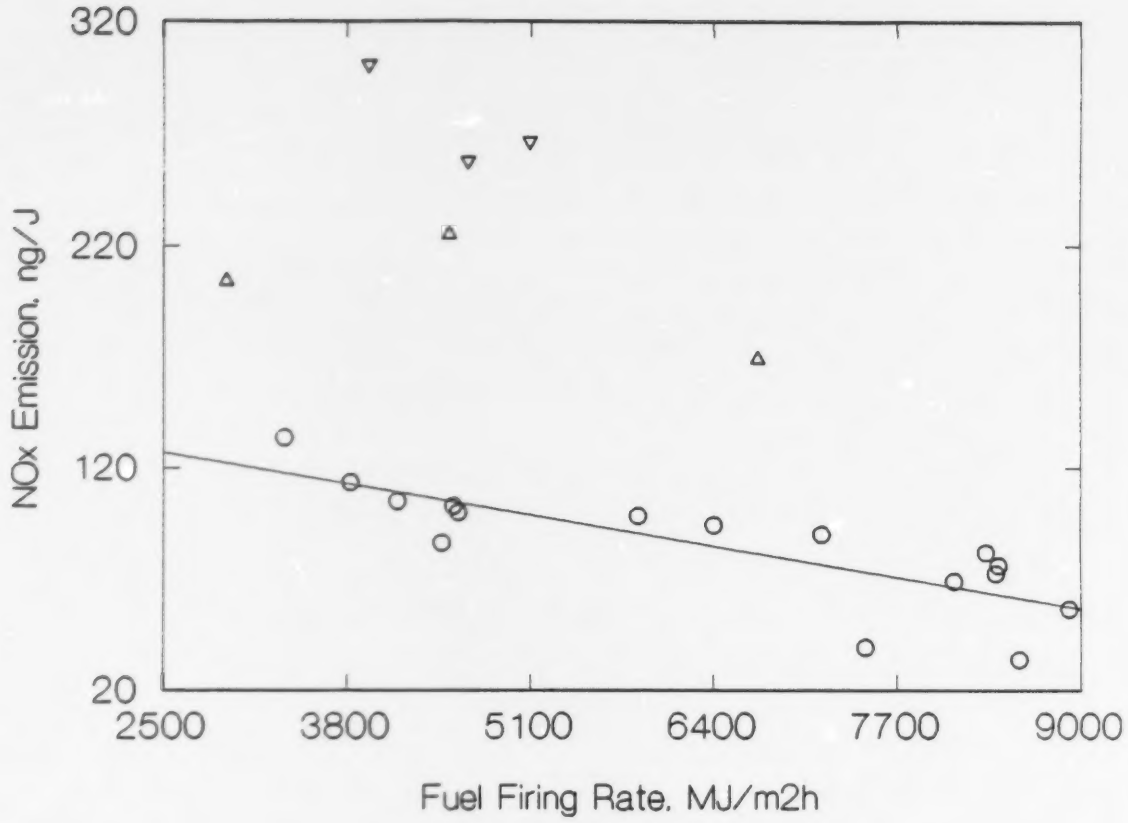

Fig. 52 Effect of fuel firing rate on NO_x emission observed in the tests with Evans coal.

Facility:
- ○ **Queen's Univ. bubbling FBC**
- △ **Summerside heating plant, CANMET tests**
- ▽ **Summerside heating plant, US EPA**

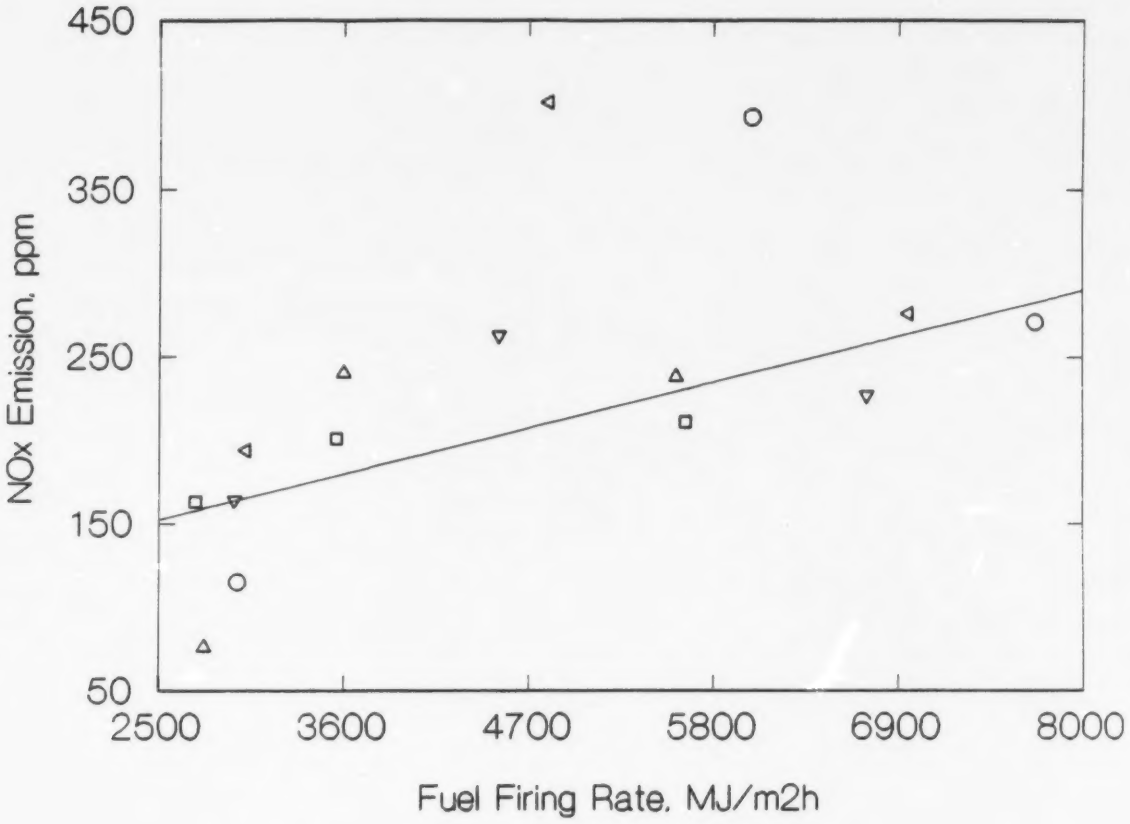

Fig. 53 Effect of fuel firing rate on NO_x concentration in flue gas observed at Summerside heating plant.

Coal: ○ Minto △ Devco ▽ Evans
□ Brogan ◁ Novaco

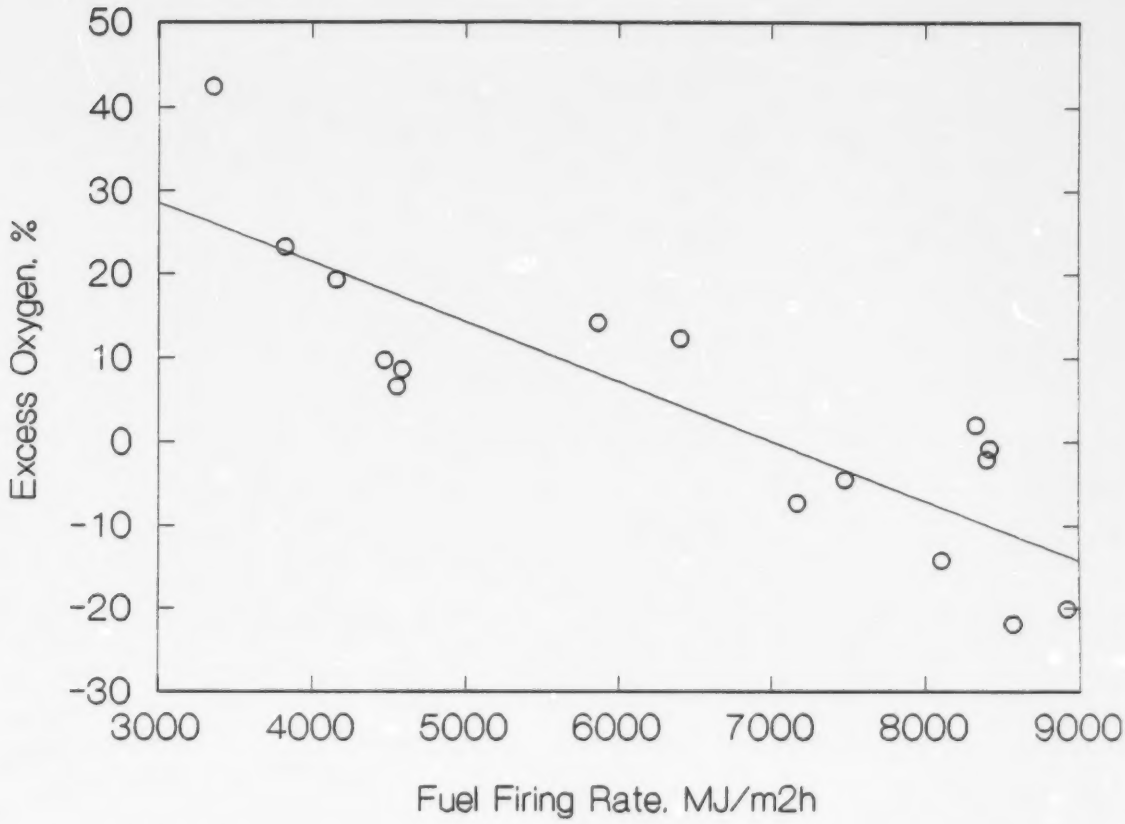

Fig. 54 Correlation between excess oxygen level and fuel firing rate observed in Evans coal tests at Queen's Univ. bubbling FBC pilot plant.

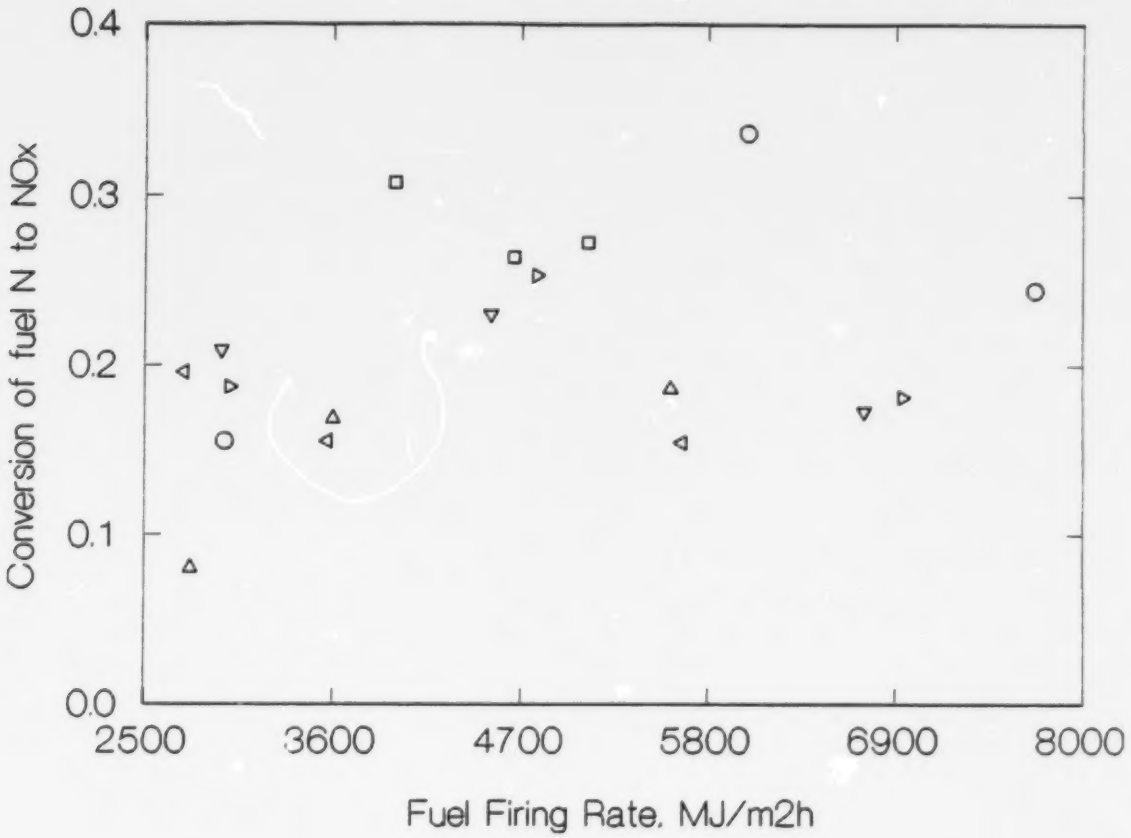

Fig. 55 Effect of fuel firing rate on conversion of fuel N to NO_x observed at Summerside heating plant.

Coal:					
	○	Minto	△	Devco
	◁	Brogan coal	▷	Novaco
	▽	Evans, CANMET tests	□	Evans, US EPA tests

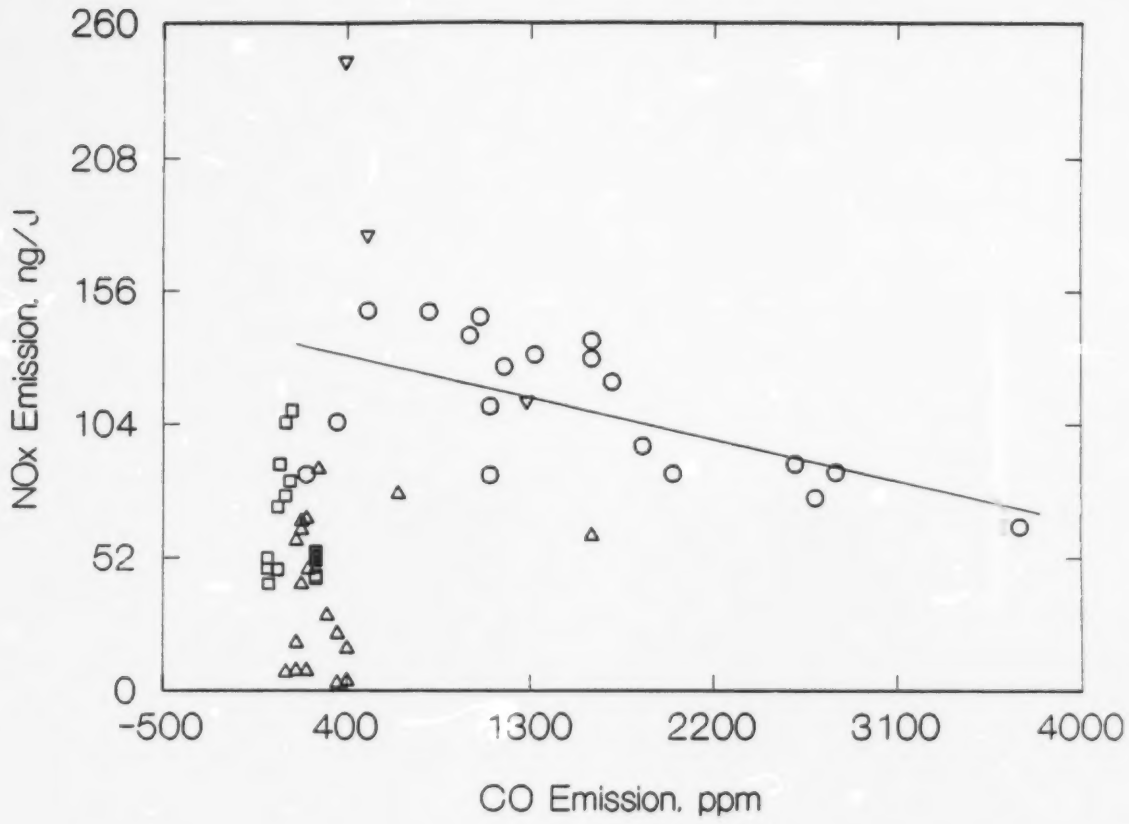

Fig. 56 Effect of CO emission level on NO_x emission of Minto coal.

Facility:
- ○ Queen's Univ. bubbling FBC
- △ Mark I bubbling FBC
- ▽ Summerside heating plant
- □ UBC circulating FBC

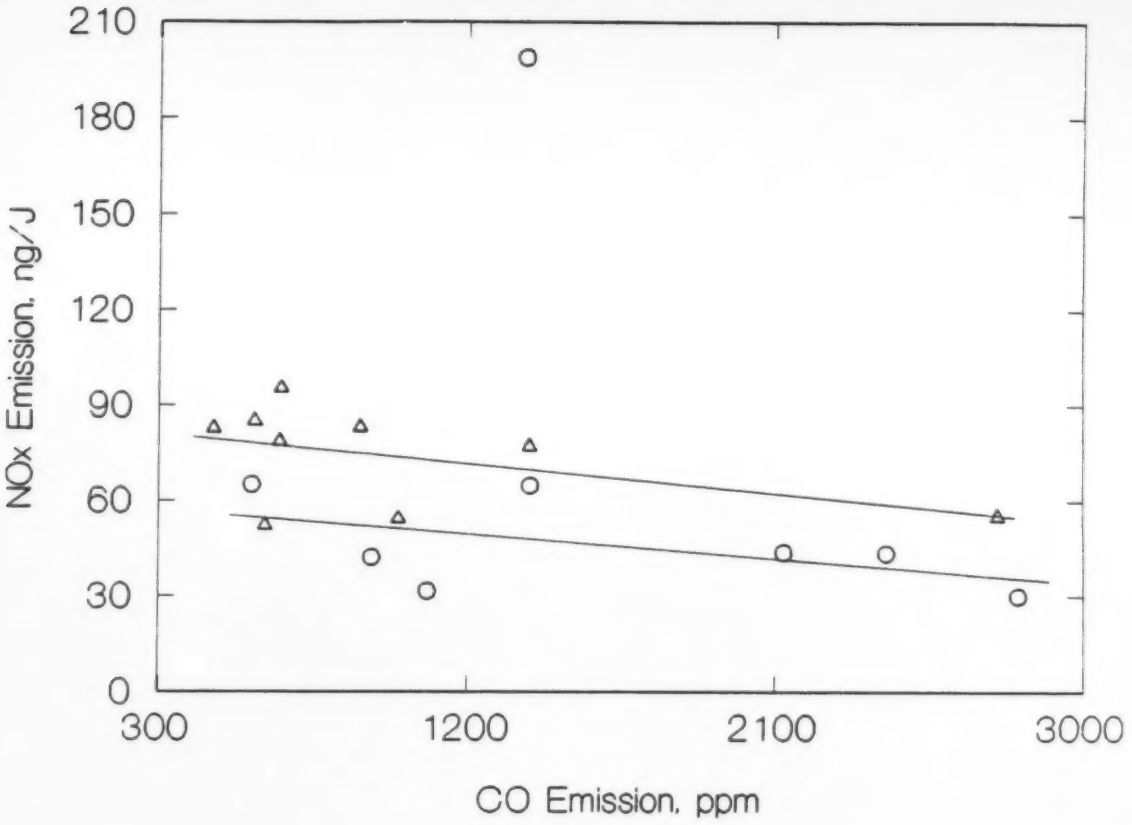

Fig. 57 Effect of CO emission level on NO_x emission of Onakawana lignite.

Facility: ○ Mark I bubbling FBC
△ Mark II bubbling FBC

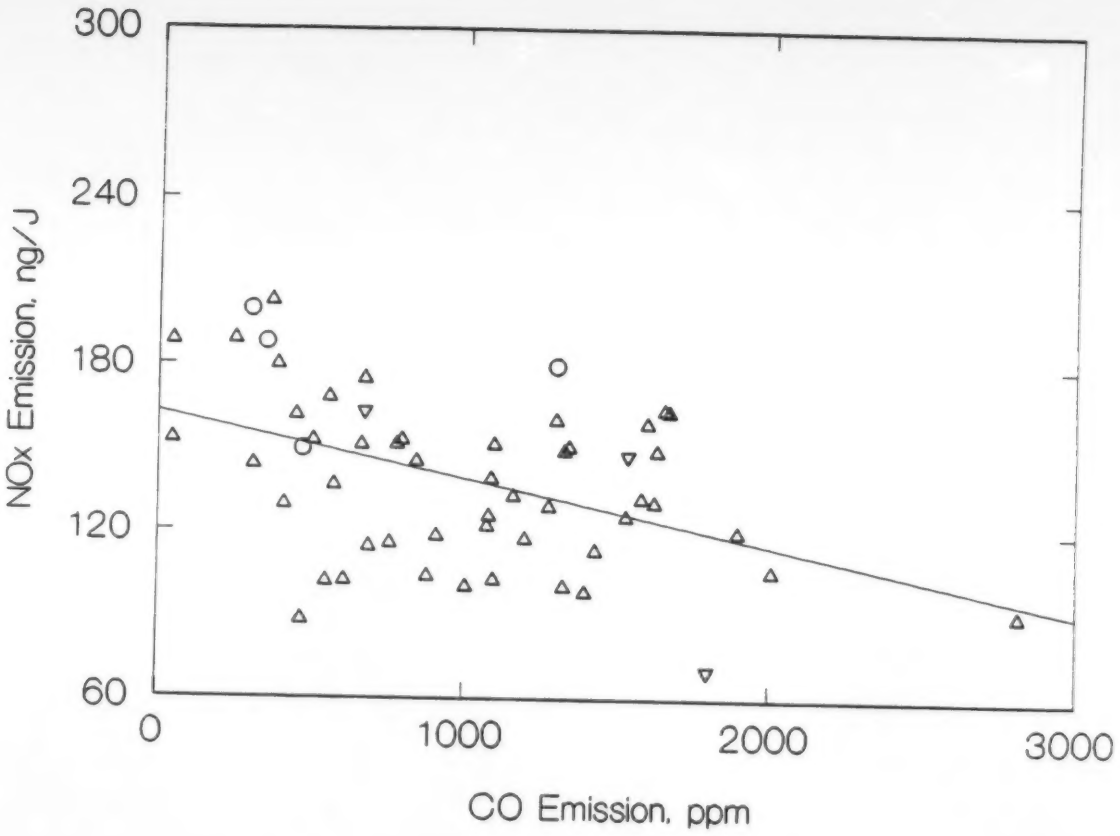

Fig. 58 Effect of CO emission level on NO_x emission of Devco coal.

Facility:
- ○ Queen's Univ. bubbling FBC
- △ Mark II bubbling FBC
- ▽ Summerside heating plant

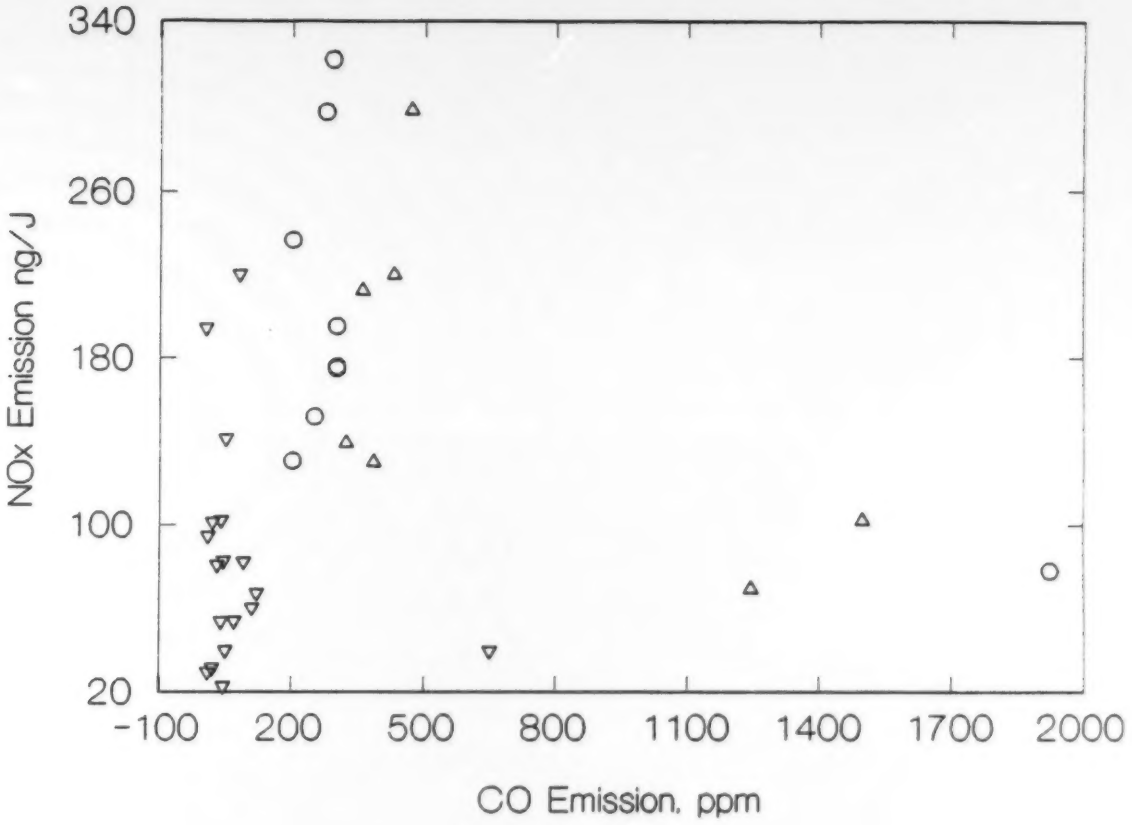

Fig. 59 Effect of CO emission level on NO_x emission of Syncrude coke.

Facility: ○ Queen's Univ. bubbling FBC
△ Mark II bubbling FBC
▽ circulating FBC in Finland.

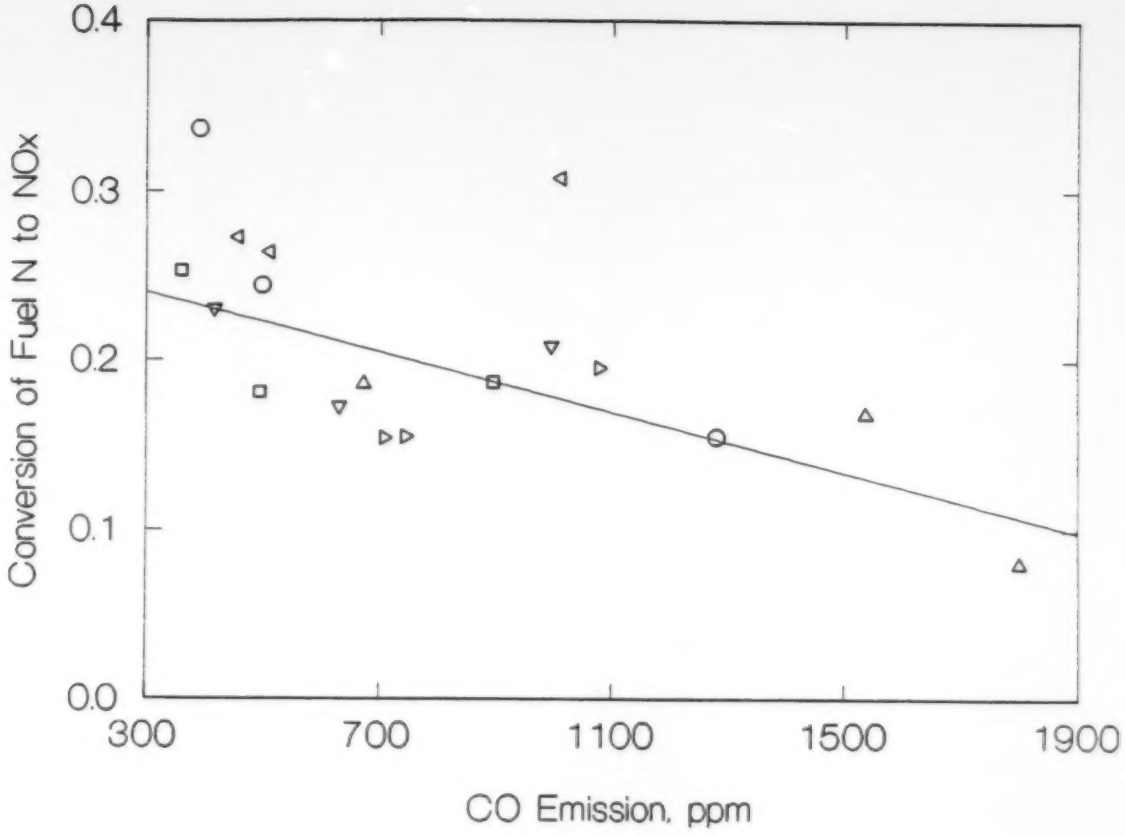

Fig. 60 Effect of CO emission level on conversion of fuel N to NO_x observed at Summerside heating plant.

Coal:
- ○ Minto
- △ Devco
- ▷ Brogan
- □ Novaco
- ▽ Evans, CANMET tests
- ◁ Evans, US EPA tests

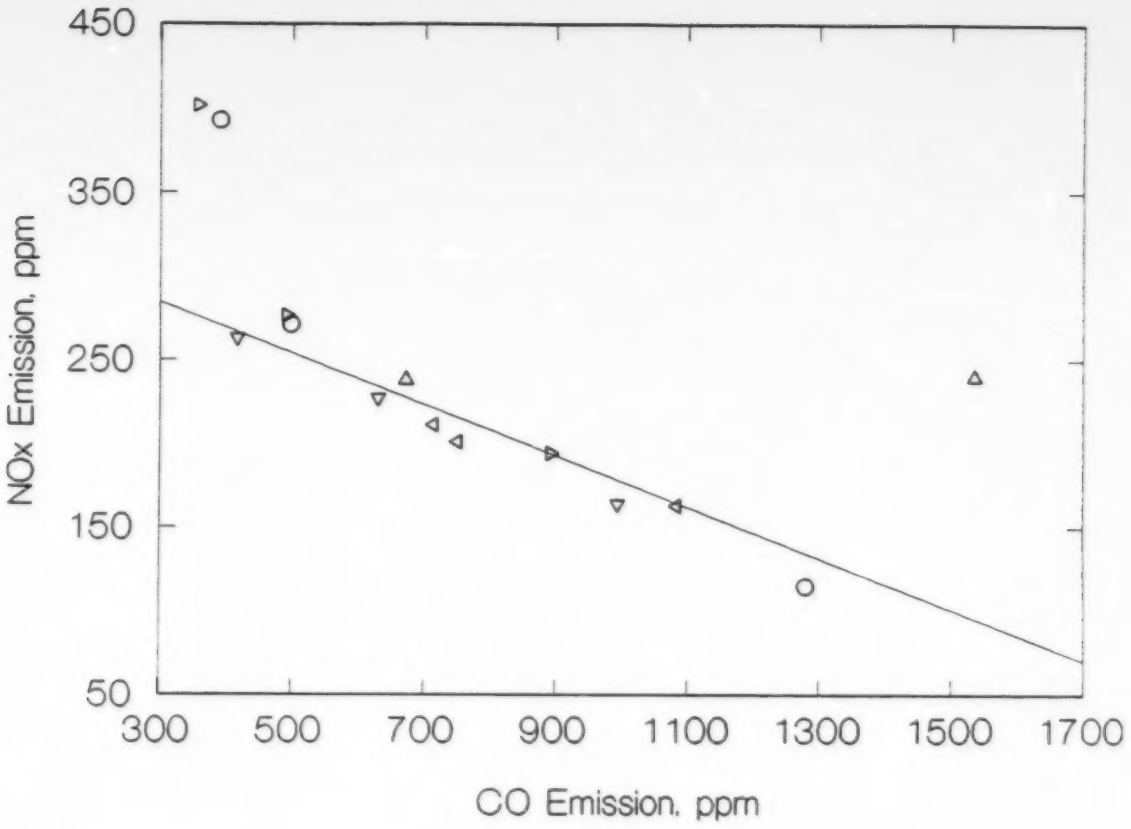

Fig. 61 Correlation between CO and NO_x concentrations in flue gas observed at Summerside heating plant.

Coal: ○ Minto △ Devco ▽ Evans
◁ Brogan ▷ Novaco

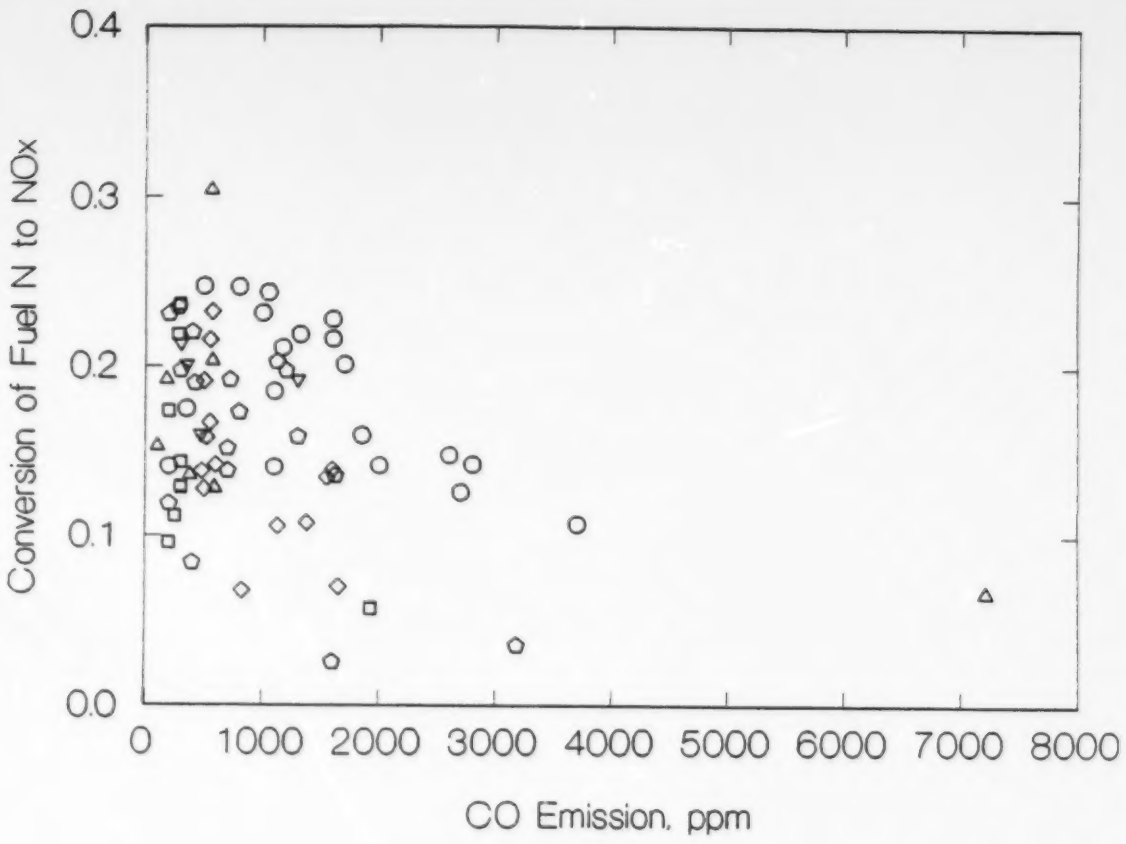

Fig. 62 Effect of CO emission level on conversion of fuel N to NO_x observed at Queen's Univ. bubbling FBC pilot plant.

Fuel: ○ Minto coal △ Highvale coal
▽ Devco coal ⬠ coal/water slurry
□ Syncrude coke ◇ Saskatchewan petroleum coke

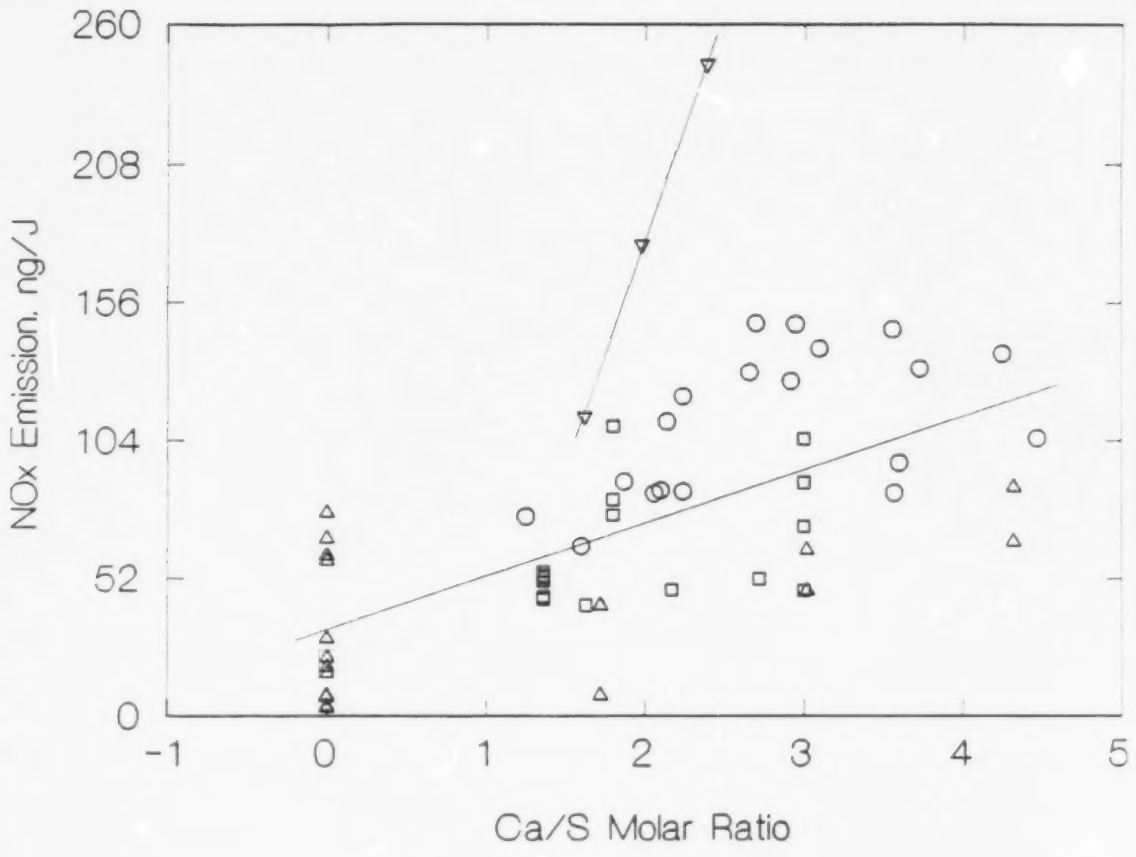

Fig. 63 Effect of Ca/S molar ratio on NO_x emission of Minto coal.

Facility:
- ○ Queen's Univ. Lubbling FBC
- △ Mark I bubbling FBC
- ▽ Summerside heating plant
- □ UBC circulating FBC

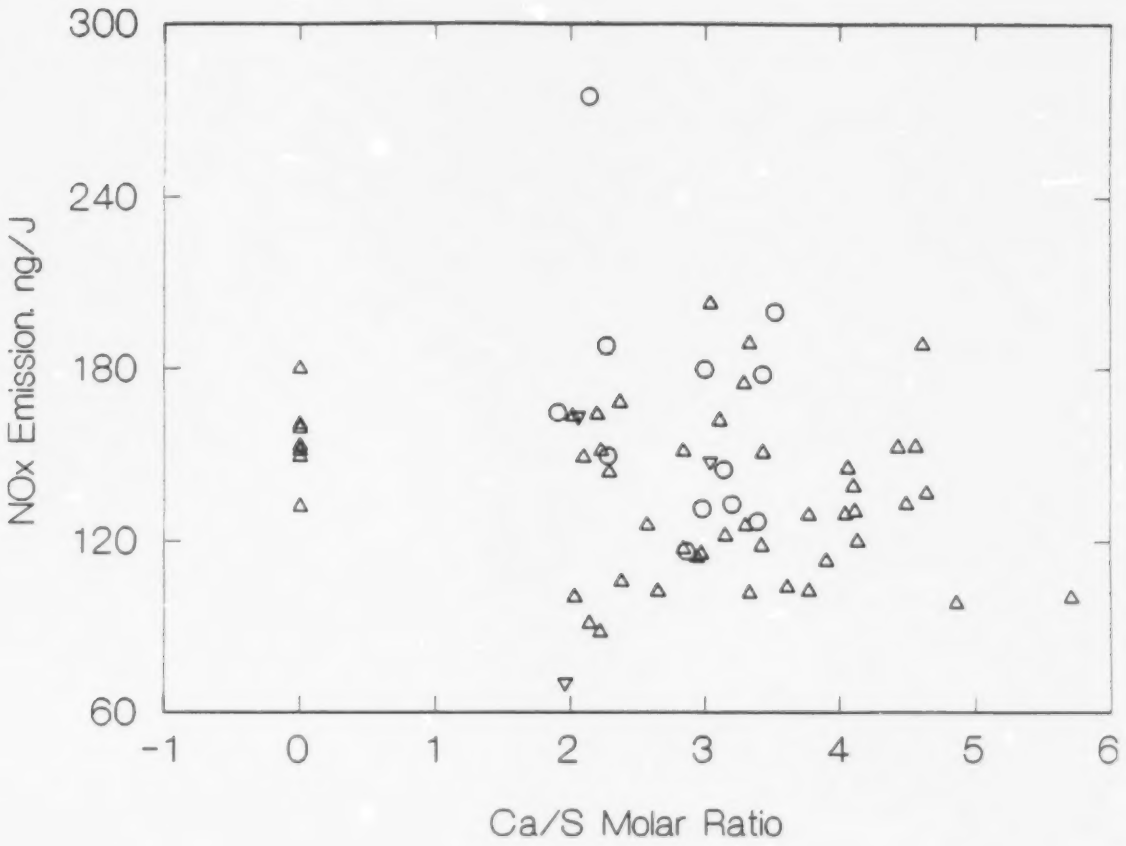

Fig. 64 Effect of Ca/S molar ratio on NO_x emission of Devco coal.

Facility: ○ **Queen's Univ. bubbling FBC**
◇ **Mark II bubbling FBC**
▽ **Summerside heating plant**

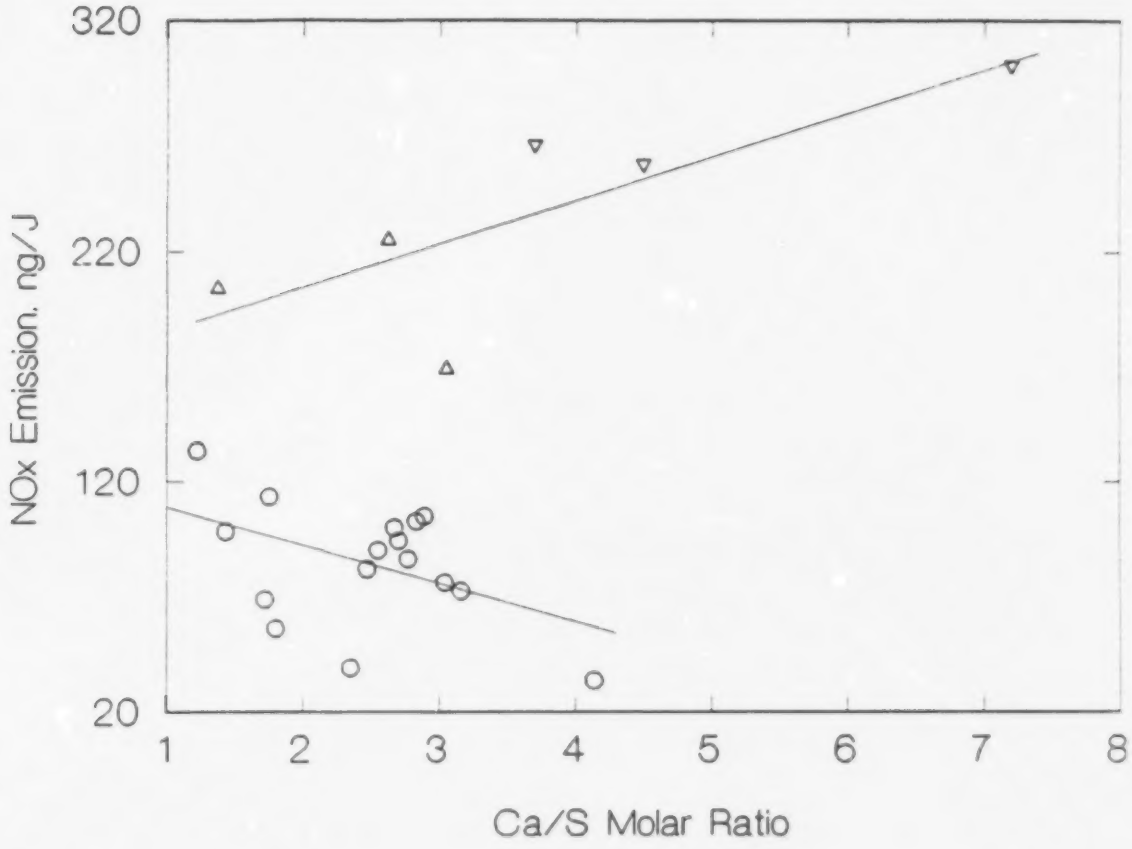

Fig. 65 Effect of Ca/S molar ratio on NO_x emission of Evans coal.

Legend:
- ○ Queen's Univ. bubbling FBC
- △ Summerside heating plant, CANMET tests
- ▽ Summerside heating plant, US EPA tests

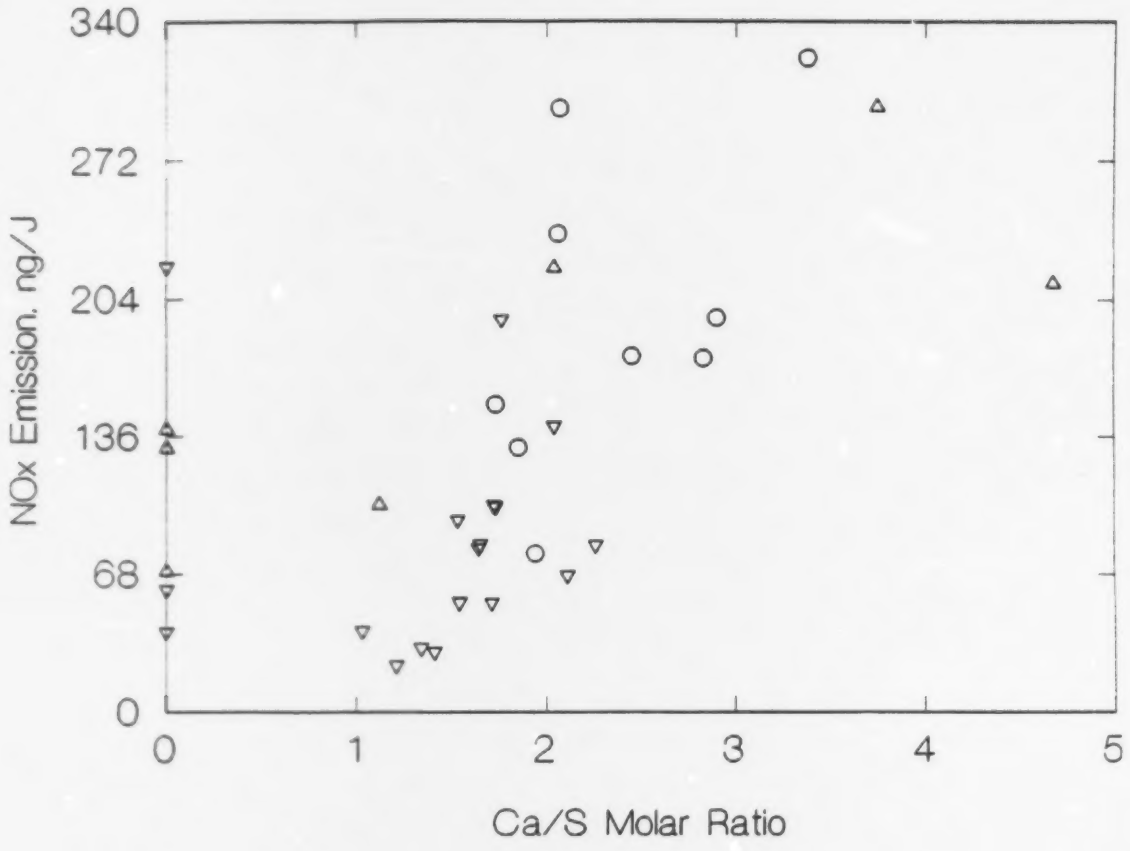

Fig. 66 Effect of Ca/S molar ratio on NO_x emission of Syncrude coke.

Facility: ○ **Queen's Univ. bubbling FBC**
△ **Mark II bubbling FBC**
▽ **circulating FBC in Finland.**

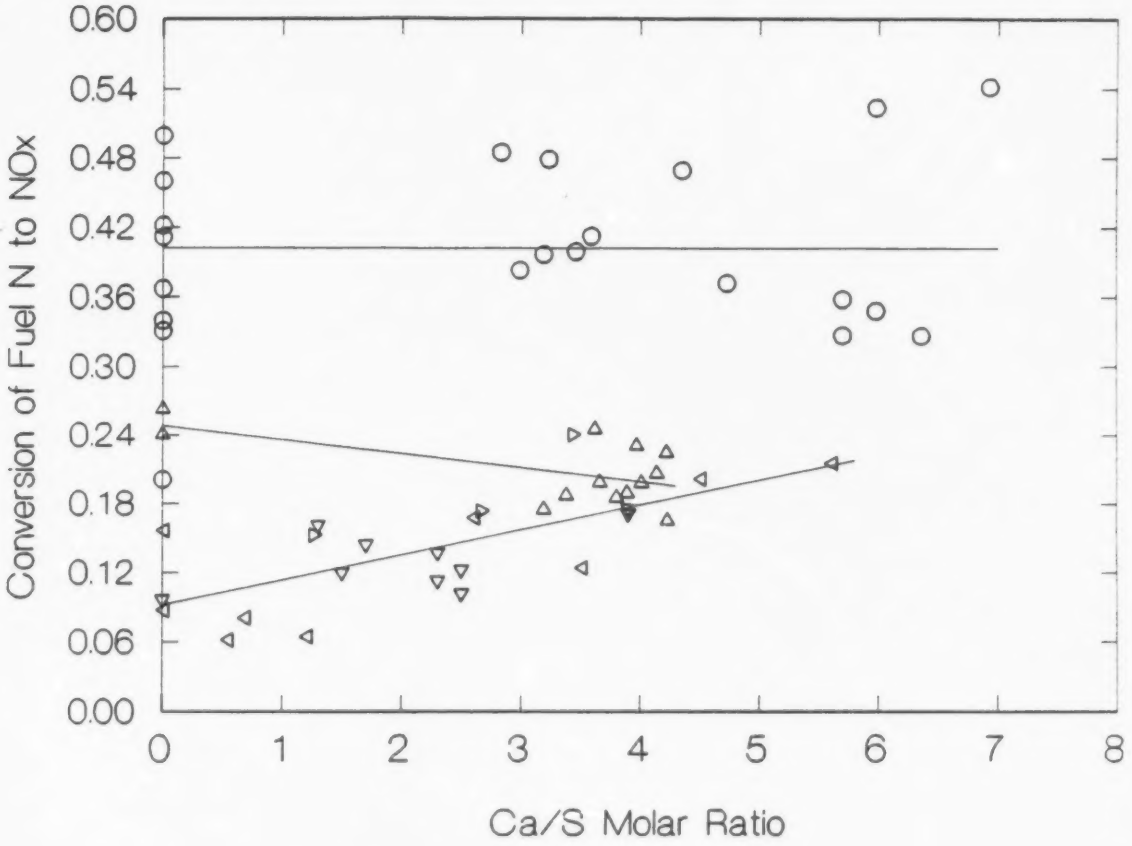

Fig. 67 Effect of Ca/S molar ratio on conversion of fuel N to NO_x of heavy oils.

Legend:
- ○ #6 oil, Mark II bubbling FBC
- △ CANMET pitch, Mark II bubbling FBC
- ▽ CANMET pitch, UBC circulating FBC
- ◁ H-oil pitch, UBC circulating FBC
- ▷ bitumen, Mark II bubbling FBC

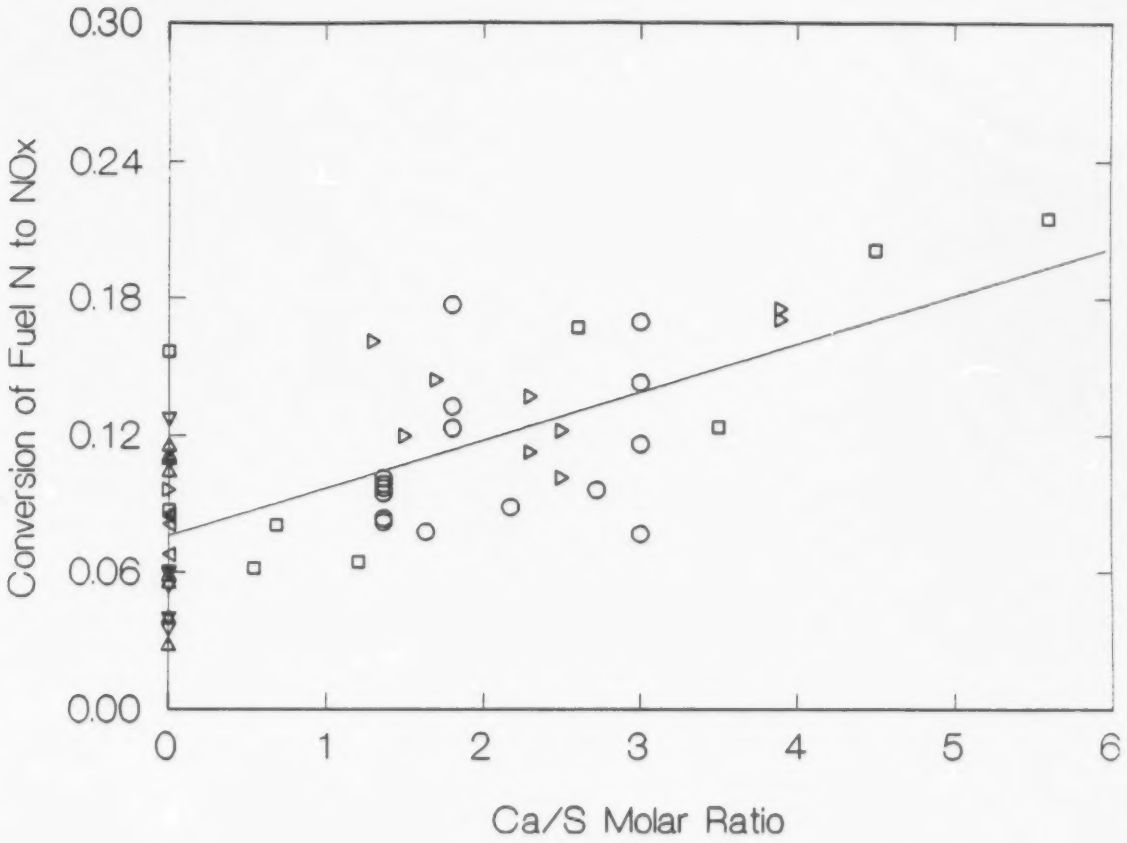

Fig. 68 Effect of Ca/S molar ratio on conversion of fuel N to NO_x observed at UBC circulating FBC pilot plant.

Fuel: ○ Minto coal △ Highvale coal
▽ Mt Klappan coal ◁ Poplar River lignite
▷ CANMET pitch □ H-oil pitch.

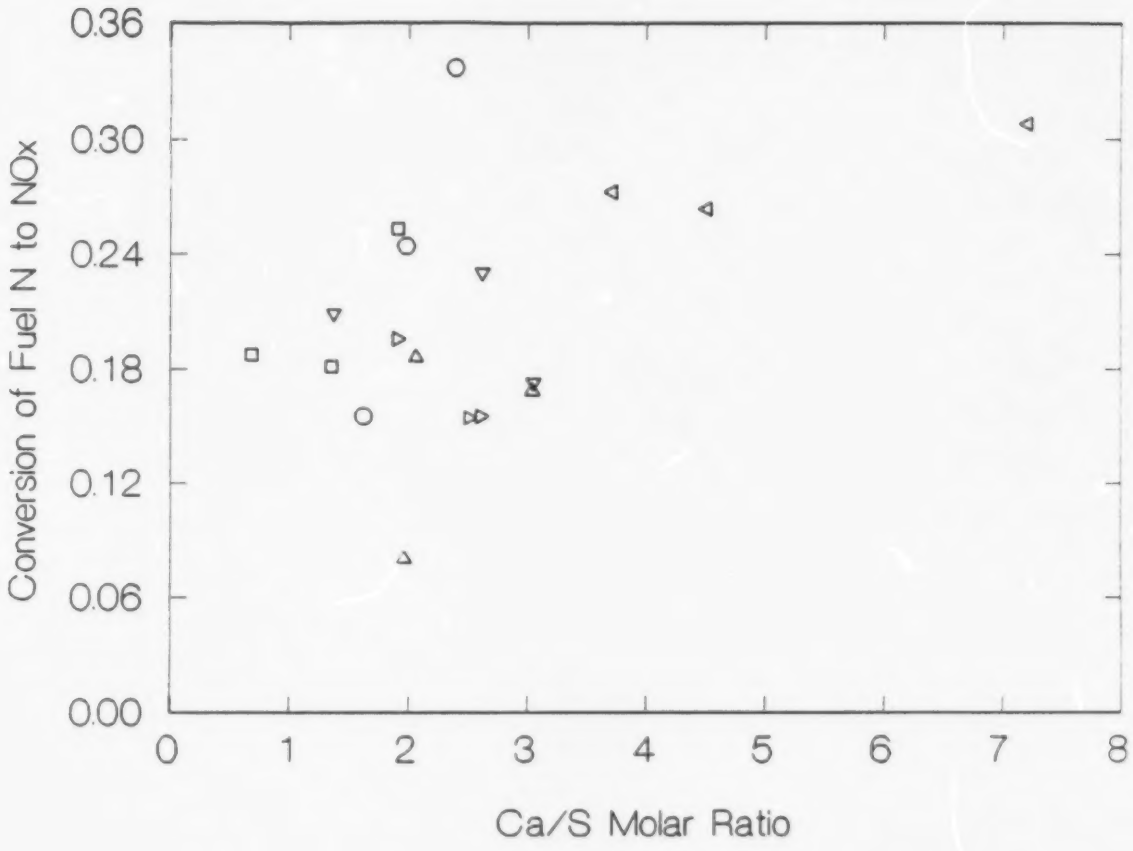

Fig. 69 Effect of Ca/S molar ratio on conversion of fuel N to NO_x observed at Summerside heating plant.

Coal:
- ○ Minto
- ▷ Brogan
- ▽ Evans, CANMET tests
- △ Devco
- □ Novaco
- ◁ Evans, US EPA tests

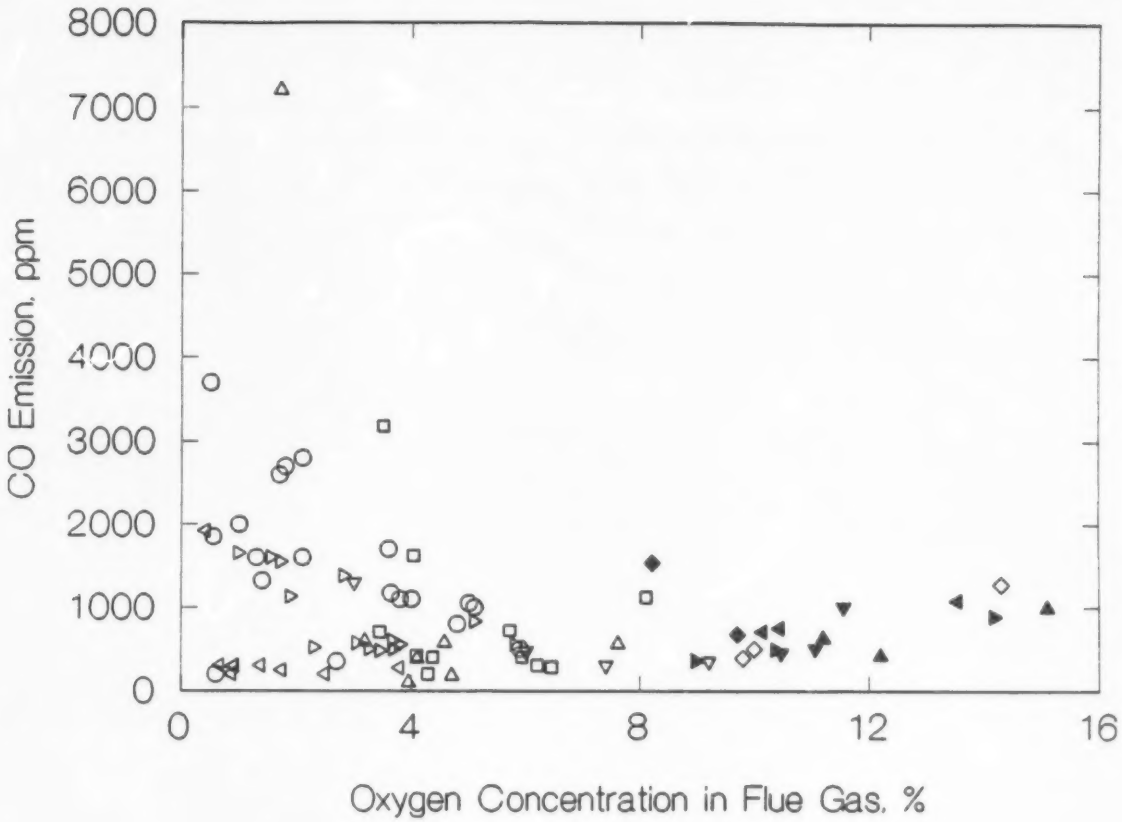

Fig. 70 Effect of O_2 level in flue gas on CO emission Observed at Queen's Univ. bubbling FBC pilot plant and Summerside heating plant.

Legend: Queen's
- ○ Minto coal
- ▽ Devco coal
- △ Highvale coal
- ◁ Syncrude coke
- ▷ Saskatchewan petroleum coke
- □ coal/water slurry

Summerside
- ◇ Minto coal
- ● Devco coal
- ◀ Brogan coal
- ▶ Novaco coal
- ▲ Evans coal, CANMET tests
- ▼ Evans coal, US EPA tests